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RADAR ANALYSIS OF THE MOON

PHASE I FEASIBILITY OF
LABORATORY
SIMULATION

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FINAL REPORT
CONTRACT NO. AF 19(628)-480

AFCRL - 62-1120

RADAR ANALYSIS OF THE MOON
Phase I: Feasibility of Laboratory Simulation

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Contract No. AF 19(628)-480

Project No. 7698

Task No. 769803

FINAL REPORT

November 30, 1962

Prepared for

GEOPHYSICS RESEARCH DIRECTORATE

AIR FORCE CAMBRIDGE RESEARCH LABORATORIES

AIR FORCE OFFICE OF AEROSPACE RESEARCH

UNITED STATES AIR FORCE

BEDFORD, MASSACHUSETTS

FOREWORD

Contract No. AF 19(628)-480 was awarded to Texas Instruments Incorporated in May 1962. The award was made in response to an unsolicited proposal, prepared and submitted by Texas Instruments, which outlined a study directly supporting the lunar research program of the U. S. Air Force. The basic objectives of the proposed study included assessment of radar potentialities for future lunar exploration and establishment of guides for selecting optimum radar frequencies for specific-property lunar determinations. The proposed work consisted of the following phases:

Phase I - Simulation Requirements and Recommendations

Phase II - Final Program Design, Implementation and Conduct

Phase III - Radar Evaluation.

The subject contract covered Phase I and provided for six and a half man months of effort distributed over seven calendar months. Phase I work, discussed in this report, deals primarily with theoretical analyses of the effects of lunar environmental conditions on radar propagation and the feasibility of simulating radar analysis of possible lunar surface materials in a terrestrial laboratory.

The principal contributors to this study and their areas of specialization and industrial or academic affiliation are shown below. Participation in data collection, analysis and project guidance was considered in making the percentage-of-contribution estimates.

Frank E. Kinsman (Electrical Engineer - Texas Instruments)	...	Environmental Studies and Theoretical Analysis	35%
Dr. Jack R. Van Lopik (Geologist - Texas Instruments)	...	Project Management and Technical Counsel	20%
Carroll W. Chapman (Consulting Electrical Engineer - Electrical Engineering Research Laboratory, University of Texas)	...	Theoretical Analysis	15%

Charles W. Lancaster (Geologist - Texas Instruments)	...	Simulation Facilities	10%
Dr. B. M. Fannin (Consulting Electrical Engineer - Electrical Engineering Research Laboratory, University of Texas)	...	Technical Counsel and Theoretical Analysis	5%
Dr. A. H. LaGrone (Consulting Electrical Engineer - Electrical Engineering Research Laboratory, University of Texas)	...	Technical Counsel and Theoretical Analysis	5%
William Jurek (Electrical Engineer - Texas Instruments)	...	Engineering Studies	5%
K. Raymond Burson (Chemist - Texas Instruments)	...	Environmental Studies	5%

Consulting services were also provided, on an informal basis, by Drs. F. S. Johnson and A. J. Dessler, atmospheric physicists associated with the Earth and Planetary Studies Laboratory of the Graduate Research Center of the Southwest, Dallas, Texas. Richard E. Hohman of Texas Instruments performed the technical editing of this report.

Dr. John W. Salisbury, Chief, Lunar-Planetary Exploration Branch, AFCRL was contract monitor for the project.

TEXAS INSTRUMENTS INCORPORATED

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ABSTRACT

The future use of radar in making specific-property determinations of the lunar surface is dependent upon knowledge of (a) the effects of lunar atmospheric conditions on radar propagation/operation and (b) radar reradiation signatures of possible lunar surface materials. If assessment of radar potentialities for exploration of the moon is to be made, theoretical analyses must be performed to determine possible effects that might be produced on radar propagation/operation if extreme-value estimates for lunar environmental factors are assumed to be correct. Based on currently available data and methods of analysis, such effects are shown to be relatively minor. In view of this determination and the embryonic status of radar terrain analysis, (which does not permit reliable interpretation of detailed measurements), fairly gross radar reradiation measurements of postulated lunar materials can be of great value. Radar frequencies at or near X-band (3 cm) and far-field operation are best suited for obtaining these data. Relatively simple facilities appear adequate, but radar reradiation measurements and theoretical determinations might require verification in a facility capable of simulating selected lunar atmospheric and surface conditions. In either case, it appears desirable and feasible to simulate radar analysis of the moon using state-of-the-art radar facilities and postulated lunar surface materials.

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SECTION I

INTRODUCTION

A. HISTORICAL WORK ON APPLICATION OF RADAR TO TERRAIN ANALYSIS

Radar itself is a comparatively recent technology (1904),[70*] but the application of radar to terrain analysis is even newer. Perhaps the earliest attempt to use radar for a form of terrain analysis was in 1947 when H. P. Smith constructed a radar map of the northwestern coast of Greenland.[102] It was not until the mid-fifties, however, that interest in the use of radar for terrain analysis became more than academic.

The inherent capability of radar for such work is based upon the fact that when an electromagnetic wave is interrupted by any substance, it induces electron motion within that substance, which in turn, reradiates the absorbed energy. This reradiation (which is a function of permittivity, permeability, and conductivity and commonly associated with the somewhat artificial term, reflection coefficient) will have a characteristically different phase and amplitude than that of the incident radiation. Therefore, when compared with known incident energy, reradiation can provide clues concerning the properties of a substance. Generally speaking, in analyses of terrain materials, the longer the electromagnetic wavelength, the deeper will be the penetration below the surface. Hence reradiation contributions from subsurface materials become evident; i.e., subsurface features can be analyzed by electromagnetic methods at depths proportional to wavelength. Furthermore, radar has a surveying capability such that time (or distance), azmuthal and elevation angles can be used in mapping applications, as foreseen by H. P. Smith. Factors such as angle of incidence, polarization and environment are also major considerations in actual field work, but it is essentially the above-mentioned inherent capabilities which make radar a useful tool for remote terrain analysis.

B. HISTORICAL APPROACHES TO THE ANALYSIS OF THE MOON

What has been stated for radar is generally true for all electromagnetic radiation. By utilizing such radiation, man has been observing the moon from the earth for thousands of years (primarily in the visual spectrum). The actual knowledge gained by such observations is astonishingly meager.[55] Hypotheses have come cheap, but knowledge is still at a premium.

* Reference Number

The reason for this lack of knowledge can undoubtedly be blamed on (1) the relative lag in the development of suitable instruments, and (2) three factors associated with utilizing the earth as an observation platform; namely

The distance between the earth and the moon, which heretofore could not be traversed,

The distortions due to the earth's atmosphere, and

The fact that only slightly more than half of the moon's surface is visible.

Nonetheless, many useful experiments and studies have been, and are being, conducted utilizing three distinct approaches. These approaches are (1) continued earth-based observations using instrumentation which now extends the useful portion of the spectrum from radio through visual,[55] (2) use of environmental chambers in which a few postulated lunar conditions are simulated,[71] (3) determination of the physical constants of materials which might compose the lunar surface.[45, 76, 112]

C. THE APPROACH OF THIS STUDY

Tremendous advances have been made in instrumentation during the last quarter century due to the pressures of war. The advent of orbital satellites, however, has undoubtedly initiated a period of scientific discoveries unequaled in importance to the selenologist. Since space flight has been proved feasible, many people aware of radar capabilities have proposed lunar orbiting vehicles with radar as the remote sensor.[31, 109] Such instrumentation would immediately remove the three difficulties associated with utilizing the earth as an observation platform.

However, a major problem associated with a radar satellite approach is cost; i.e., if the launching missile fails or if the effects of lunar environmental factors completely degrade the returned electromagnetic terrain analysis data, many dollars are wasted. Therefore, every reasonable precaution must be taken to insure success of the mission. Such systems should be checked out as thoroughly as possible on earth before a lunar mission is initiated, but analytical studies are by themselves inadequate. The problems confronted in space operation are so immense, both in complexity and in quantity, that many people have expressed opinions that the use of space simulation chambers is the only practical solution to the problem.[19, 60, 96]

But, how completely can a space environment be simulated? Equally important, how completely must it be simulated in order to test all the critical features of space exploration?

This study is an attempt to provide an answer to these questions for the limited problem of radar analysis of the moon. The question then becomes, "Is it feasible to simulate radar analysis of the moon?"

The above considerations led to the following approach in this study:

A literature survey to identify the extreme conditions which might require simulation

A theoretical analysis of these conditions to demonstrate which ones must be simulated

An engineering study to test the feasibility of simulating the necessary environmental factors

A survey of simulation facilities to determine if some existing facility might be used or modified to meet requirements

SECTION II

SURVEY OF LUNAR ENVIRONMENTAL FACTORS

A. EXTENT OF SURVEY

A literature search, by its very nature, never has a natural concluding point and constantly requires up-dating. However, more than 150 documents were surveyed in the present study (the majority of which are included in the bibliography).

B. SURVEY RESULTS

It probably would be difficult to find any other "scientific" area of endeavor having more conflicting and confused hypotheses than those connected with lunar studies. This can be seen readily in Appendix A, a collection of pertinent quotations which summarize the environmental literature survey. These quotations have been grouped under five major headings: temperature, large and small scale surface features, atmosphere, magnetic field, and dimensions.

1. Atmospheric Factors Which Might Affect Radar Analysis of the Moon

One item which seems to be conspicuous by its absence in all previous considerations of radar operations in the vicinity of the moon is the effects of postulated lunar environmental factors on propagation. Until an analysis has been conducted on the factors associated with the lunar environment which might influence propagation of electromagnetic energy, all experimental work using electromagnetic propagation in any form will be open to serious question. Such determinations certainly cannot be made in finality within the scope of this report. In fact, it is unlikely that they could ever be settled using the meager and conflicting data currently available. However, in order to provide guide lines for environmental simulation considerations and other future work, pertinent factors were selected from Appendix A and other sources. This led to the compilation of Tables I and II.

The method used in selecting values for inclusion in these tables was not one of trying to make the "best choice" (such selection processes must be subjective and therefore, always open to question), but rather one of selecting extreme estimates as given by various authors. These factors, in Tables I and II, were examined theoretically to determine their effect on radar propagation (see Section III).

TABLE I

REPORTED EXTREMES OF SELECTED LUNAR AND TERRESTRIAL ATMOSPHERIC FACTORS

	MOON	EARTH
Temperature	(52)* (92) 1027° to -183° C	(110) (110) 58° to -88° C
Particle Bombardment	(46) (46) 10^{12} to 10^{8} protons/cm^2-sec	(15) (15) 7 x 10^{-1} to 5 x 10^{-4} protons/cm^2 - sec - sterad
Atmospheric Density	(20) < 10^{10} molecules/cm^3	(83) (113) 2.7 x 10^{9} to 9.1 x 10^{5} molecules/cm^3
Atmospheric Pressure	(35) (45) 0.076 to 10^{-16} mm Hg	(15) (15) 792 to 730 mm Hg
Micrometeorite Flux Density	(113) 10^{-9} particles/cm^2 - sec (> a few microns)	(89) 10^{-6} particles/cm^2 - sec
Molecular Mean Free Path		(83) (83) 3 x 10^{9} to 9 x 10^{-6} cm
Electron Density at Surface	(92) (92) 10^3/m^3 to 10^7/cm^3	(15) 2 x 10^{-2}/cm^2 - sec - sterad
Electron Collision Frequency		(83) (113) 9.5 x 10^{11} to 80/sec
Atmospheric Constituents	(73) Helium Krypton Xenon Argon Radon Neon Water Vapor Mercury Vapor (48) Sulphur Dioxide Carbon Dioxide	(2) Nitrogen Oxygen Argon Carbon Dioxide Neon Helium Methane Krypton Nitrous Oxide Carbon Monoxide Xenon Water Vapor
Magnetic Field	(35) (73) 3000 to 2.5 gammas	(15) (15) 60,000 to 25,000 gammas
Gravity	(72) 155 cm/sec^2	980 cm/sec^2

* Reference Number

TABLE II

REPORTED EXTREMES OF SELECTED LUNAR AND TERRESTRIAL SURFACE AND SHALLOW-SUBSURFACE FACTORS

	MOON	EARTH
Temperature Surface	(92)* (92) 134° to -183° C	(110) (110) 58° to -88° C
Near Surface	(106) -23° C	(59) 11° C (20-200')
Dust Thickness	(45) (73) 0 to an average of 1 km	
Dielectric Constant	(26) (76) 2.7 to 1.1 ϵ_o	(15) (15) 85 to ~2 ϵ_o
Thermal Conductivity	(14) (38) < 10^{-4} to 5 x 10^{-6} calories/sec-cm-deg	(49) (49) 0.5 to 3.3 x 10^{-4} calories/sec-cm-deg
Electrical Conductivity	(76) (76) 4.8 x 10^{-4} to 3.4 x 10^{-4} mhos/m	(69) (83) 10^{-1} to 10^{-17} mhos/m
Electrical Permeability	(76) (14) 1.4 to ~1.0	(49) ~1000 (high purity iron)
Electron Density at Surface	(92) (92) 10^3 /m^3 to 10^7/cm^3	(15) 2 x 10^{-2}/cm^2-sec-sterad
Surface Elements	(82) Iron, Silicon, Magnesium, Aluminum, Oxygen, Potassium, Calcium, Neon, Nickel; (8) Titanium; (4) Unknown	All known
Glaciers	(64) (51) 300 to 0 feet thick	(2) 8000 to 0 feet thick
Particle Bombardment	(46) (46) 10^{12} to 10^8 protons/cm^2-sec	(15) (15) 7 x 10^{-1} to 5 x 10^{-4} protons/cm^2-sec-sterad
Surface Charge	(79) (79) 40 to 0 volts positive	0 volts (normally)
Topographic Relief Small Scale	(91) (45) 1.0 m to 0.1 mm	mm up
Large Scale	(56) Up to 19,550 feet	Up to 29,000 feet
Slopes	(57) 46 plus to 0 degrees	(33) 75 plus to 0 degrees
Magnetic Field	(35) (73) 3000 to 2.5 gamma	(15) (15) 60,000 to 25,000 gamma
Gravity	(72) 155 cm/sec^2	980 cm/sec^2

* Reference Number

Such an analysis provides results which demonstrate that, even in the extreme, certain factors will not affect propagation while others affect it by varying amounts. Obviously the noncontributing factors can be ignored in a simulation process. The remaining contributors required consideration from an engineering standpoint (see Section IV) to determine the feasibility of simulating these environmental factors.

Only after these analyses were completed was subjective reasoning applied to the feasibility of simulating radar analysis of the moon in a terrestrially-based simulation laboratory (see Section V).

2. Surface and Shallow-Subsurface Factors Which Might Affect Radar Analysis of the Moon

Many features of lunar materials will affect radar analysis of the moon. For example, the selection of radar for lunar analysis is based on the assumption that subsurface information will be available in a radar output. This is usually true, however, penetration of electromagnetic radiation is a function of the conductivity of the "soils." Any good conductor exhibits a "skin effect" which becomes more pronounced as frequency increases; i.e., current flow is trapped in the outer surfaces of the conducting body and consequently there is little or no penetration into the body. Therefore, if there should prove to be a highly conductive body (or soil) near the lunar surface (as postulated by Gibson, Wehner and others), depth of penetration would be restricted. Subsurface mapping would be extremely difficult under such circumstances.

As mentioned previously, permeability, permittivity and conductivity all affect electromagnetic propagation. Therefore, the actual lunar surface and shallow-subsurface materials are very important considerations in radar analysis of the moon. Not only must their characteristic returns be identified, but their effects in combination (as illustrated in the preceeding example) must be considered. For these reasons, Table III was prepared from the information presented in Appendix A and will be used in future experiments and analyses (see Section IIIB).

TABLE III

REPORTED LUNAR SURFACE AND SHALLOW-SUBSURFACE MATERIALS

Material	Depth	Possible Condition of Material Found on Lunar Surface
A. UPPERMOST LAYER		
IGNEOUS ROCKS		
Ultrabasic Rock	No Data	Serpentines More basic than earth's
Basalt	No Data	Pulverized
Volcanic Extrusives		
Pumice	Variable	Spongy and porous Disrupted
Tuff	No Data	No Data
Froth Material	No Data	Sintered Low density Homogeneous Slag-like Hard porous [like] cotton-wool Half as dense as water Metal rich residue Large vesicle size
SANDS		
Undifferentiated	1 to 10 cm	Dry terrestrial desert 80 per cent quartz High silica 0.3 mm diameter
DUSTS		
Undifferentiated	1 km to a few feet	Interplanetary High silica Meteor dust Not loose Loose Low density Pulverized magma rock in vacuo Loosely sintered 1 to 300 micron in diameter

TABLE III (cont'd)

Material	Depth	Possible Condition of Material Found on Lunar Surface
Ash	Very thin Variable	Coarse grained
Meteoritic	Veneer to 5 cm	Chondritic composition minus 5-per cent iron
ALTERED PRODUCTS		
Sputtered Material	Few cm	No Data
Proton Bombarded Material (metallic oxides)	No Data	Fe_2O_3, etc
NOT NATURALLY OCCURRING (as found on earth)		Albedo too high (visual) Not opaque enough (visual)
Pumice Obsidian Basalt Scoria Quartz		
NO SEDIMENTARY ROCKS		
NO PRIMARY ROCKS		Based on spectrophotometric data (Halajian)
NO TEKTITES OR METEORITES (as found on earth)		Measurement of physical constants (Brunschwig)
NO EXTENSIVE SINTERING OR WELDING		Visual experimental work (Hapke)
NO OBJECTS 2.5 M TO 10 CM		"From reported experiments" (Evans)
B. INTERMEDIATE LAYER		
No Data	From 0.5 cm down Several cm or more	Good thermal and electrical conductor

TABLE III (cont'd)

Material	Depth	Possible Condition of Material Found on Lunar Surface
C. BASE LAYER		
VOLCANIC		
Basalt	Extends to considerable depth	Loose particles solid in nature
Lava (maria regions)	No Data	Highly vesicular grading downward into solid lava
BASEMENT ROCK	No Data	Highly fractured
ROCK FROTH	Extends to considerable depth	Loose particles solid in nature

SECTION III

ANALYSIS OF THE EFFECTS OF ENVIRONMENTAL FACTORS ON RADAR PROPAGATION

A. ATMOSPHERIC

1. Introduction

a. Three Modes of Propagation Considered

Near vertical incidence (corresponding to a lunar orbital vehicle propagating a restricted pattern directly beneath its orbital path.)

Near grazing incidence (corresponding to a lunar orbital vehicle propagating a pattern at an angle which brings the energy near the limb of the moon.)

Near horizontal propagation (corresponding to a lunar based radar.)

Of the three modes, the first two were given priority in the analyses.

b. Types of Propagation Effects to be Considered

A gaseous medium through which a wave propagates can influence the wave in the following ways:

Attenuate the wave - this reduction in strength may result from absorption or from wide-angle scattering.

Bend or refract the ray - this results from gradients in the velocity of phase propagation.

Scatter the energy - a distinction needs to be made between wide-angle scatter and small-angle scatter. In the latter case the major portion of the energy continues in a dominantly forward direction but becomes diffused to the extent that fine detail is obliterated.

Reflect the energy - this occurs where the characteristics of the medium change very abruptly.

Cause frequency dispersion - this results from the propagation characteristics of the medium which vary with frequency and causes waveshape distortion.

Cause polarization rotation and wave splitting - these effects are present only when the wave propagates in an ionized medium contained in a magnetic field.

In addition to these medium induced effects, other effects that fall within the scope of this investigation but are not a consequence of the characteristics of the atmospheric medium are:

Diffraction by mountain ranges and the moon's mean curvature.

Antenna effects such as impedance changes, breakdown or corona discharge and noise.

One major phase of this investigation is to provide estimates of the extent to which each constituent might contribute to different macroscopic properties of the lunar atmosphere. The other major phase is the consideration of extremes to be expected for each of the propagation effects listed above. The organization of the following analyses is in accordance with this division of concepts.

c. Methods of Analysis

1) Macroscopic Description of Matter

The interaction of electromagnetic waves with matter involves elementary charged particles arranged in atoms, molecules, etc., and in some cases free electrons. On this microscopic scale the interactions can be evaluated fully only by the concept of quantum mechanics. However, in most situations it is appropriate to employ the classical electromagnetic theory using the macroscopic properties of the medium; i.e., those properties which result from averaging over a large volume and/or time interval so that the effect of a very large number of particles is obtained. This representation is usually valid as long as the critical microscopic dimensions (such as particle size, distance between particles, mean free path, etc.) are much less than the critical macroscopic dimensions (such as "blob" size, layer thickness, etc.). When this condition is not met, the accuracy with which macroscopic quantities describe the actual situation becomes a matter of conjecture. The lunar atmosphere is predicted to be rather tenuous, but the mean distance between collisions should not inadvertently be assumed small compared with critical macroscopic dimensions. However, even in many rather extreme cases it is felt that this simplified analysis will produce results which were "in-the-right-ballpark." Thus only a macroscopic description of matter will be attempted in this report.

In the macroscopic sense, the extent to which the medium at a point in space and time interacts with an electromagnetic wave is expressed by the properties of the medium at that point. In addition to the dielectric constant and conductivity it is necessary to consider the absorption and scattering coefficients of the medium. These coefficients are based on the assumption that the wave has the character of a plane wave over small regions of space.

Energy is lost from the wave through Joule heating (due to conductivity of the medium), by absorption and by scattering. Thus for many purposes the effects of these phenomena can be combined and described by a single attenuation constant.

2) Microwave Optics (or Ray Theory)

Microwave optics gives an approximate representation of electromagnetic waves that is easy to comprehend and digest, so it is ideal for obtaining and presenting approximate solutions to propagation problems. It is based on the concept that the energy in a wave is propagated along ray paths that are everywhere perpendicular to constant phase fronts. As the energy traverses the ray path it is diminished due to Joule heating, absorption and scattering. The rate at which the field intensity decreases when considered as a proportionate amount per unit distance is defined as the attenuation constant. The rate (radians per unit distance) at which the phase shifts along the ray path is the phase constant. These attenuation and phase constants are point properties of the medium as discussed in the preceeding paragraph. In addition, the energy density increases if the flow lines (rays) converge and decreases if they diverge.

The concept of microwave optics does not need to be elaborated upon here. It should be noted, however, that propagating phase fronts are an integral part of the concept so that estimating the properties of the medium from considerations involving plane waves is appropriate. But, this concept is only approximate, so some of its more extreme shortcomings should be noted.

It is readily apparent that the results predicted in the neighborhood of a caustic (where neighboring rays cross) must be in error since infinite field strengths are not plausible, but even more pertinent to the present study is the insight gained by considering a simple diffraction example. Consider the simple 2-dimensional example in Figure IIIA-1 which shows a plane wave in a region containing an anomalous region of thickness x along the direction of propagation and height d normal to this direction, where the properties of this region differ slightly from those of the surrounding space. On a vertical plane just to the right of this region, ray theory predicts the field to be unmodified except in that portion shadowed by the anomalous region where the modification would be slight. This is a rather accurate approximation of the actual distribution. Such a field can be equated to the sum of the unmodified plane wave plus a portion that is zero except over an interval of height d. Further to the right, the field becomes the primary plane wave plus a different wave diffracted through a hole of height d in an absorbing screen. Standard diffraction theory describes such a diffracted field in terms of a near field region (Fresnel region) in which the ray picture is adequate and a far field region (Fraunhofer region) in which the energy radiates radially outward. The transition between these regions occurs in the vicinity of the distance $2d^2/\lambda$ from the diffracting screen. The conclusion to be drawn from this is that the effect of anomalous regions (in which the propagation characteristics differ only slightly from the surrounding space) is adequately described by microwave optics in the near field zone but not in the far field zone.

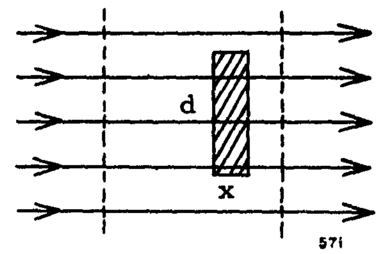


Figure IIIA-1. Diffraction Example

3) Constituents Contributing to Propagation Characteristics of a Medium

Different types of constituents in the lunar atmosphere would be expected to influence radar propagation to varying degrees, to have different frequency dependencies, etc., and contribute to the net macroscopic properties of the media. The obvious types of constituents to be considered include molecules, free charged particles (particularly electrons) and dust or aerosols.

2. Contributions of Various Atmospheric Constituents

a. Choosing the Lunar Atmospheric Parameters

On the basis of experimental and theoretical knowledge available in current literature (see Appendix A) a permanent lunar atmosphere is apt to be extremely rarefied when compared to the terrestrial atmosphere. However, this analysis was approached from the viewpoint of analyzing extreme values of the various atmospheric parameters pertinent to radar propagation calculations assigned by various authors regardless of whether they pertained to the permanent atmosphere or a transitory atmosphere. These estimated parameters were used to calculate the extreme effects of a lunar atmosphere on radar propagation. It follows that the estimates of atmospheric particle densities assigned here are those which are the upper limiting values likely to be encountered. These densities would have the greatest effect on radar propagation.

Some of the first quantitative estimates of the lunar atmospheric density were made in the mid-1940s. At that time, measurements indicated that the density was less than 10^{-4} earth atmospheres.[103] (Since the terrestrial atmospheric density at the earth's surface is of the order of 10^{19} molecules per cm^3, then 10^{-4} earth atmospheres corresponds to a density of the order of 10^{15} molecules per cm^3). As the precision of measuring techniques was increased in succeeding years, this estimate has been lowered considerably until recently studies by Elsmore and others[23] indicate that the density may be less than 10^{-13} earth atmospheres (10^6 molecules per cm^3). In substantial agreement with this figure is the estimate of Bobrovnikoff.[4] He has concluded that a permanent lunar atmosphere cannot exceed 10^{-12} earth atmospheres (10^7 molecules per cm^3). Green[103] also concurs with the order of magnitude of these estimates.

It appears that the measurement by Elsmore is the more recent. He arrived at his figure in a study of an occultation of Crab Nebula in which refraction (assumed to be due to a lunar atmosphere) was observed. The amount of refraction measured corresponded to an electron density of 10^4 per cm^3; from this figure, he inferred that the molecular density of the lunar atmosphere is less than 10^{-13} earth atmospheres. A question as to the validity of Elsmore's value of molecular density has been raised by Firsoff [34]; he assumes that Elsmore's value of electron density is derived from high-level (high altitude) atmospheric effects, but it is possible that an appreciable amount of argon may be present in the lunar atmosphere. If it is not extensively ionized by the sun's radiation, its presence will be undetected by this method.

On the other hand, if the arguments and theory of Öpik and Singer[65] are valid, then Firsoff's objection is overcome. Their studies reveal that, contrary to the predictions of the classical theory of an exosphere (see, for example, Jeans, <u>The Dynamical Theory of Gases</u>) even the heaviest inert gases will not be retained by the moon, and they conclude that "...an independent lunar atmosphere, i.e., one that evolves from the moon, cannot exist even if it consists of heavy gases such as krypton and xenon. Hence, a lunar gaseous envelope is entirely determined by the surrounding interplanetary medium." In their study Öpik and Singer showed that photoionization can have an important effect on the rate of loss of a lunar atmosphere. By considering only the radiation intensity contribution of the solar line H_e^{II} 304 they found that photoionization of the heavy gases krypton and xenon would have the effect of increasing the loss rate beyond that predicted by classical theory of an exosphere, i.e., even those gases (which are heavier than argon) are eventually lost. These conclusions tend to imply that an appreciable amount of argon cannot remain so that Firsoff's objection does not seem to be justified.

On the basis of the above information, it appears justifiable to assume that if a permanent lunar atmosphere exists it will not exceed 10^6 to 10^7 molecules per cm^3; however, the possibility cannot be overlooked that a density as low as the quiescent interplanetary level of the order of 10 to 10^2 particles per cm^3 (presumably protons and electrons) may prevail. As already pointed out, this low density will not be considered in the radar calculations since this figure is comfortably less than Elsmore's results of 10^4 electrons per cm^3 and 10^6 molecules per cm^3.

Even though a permanent envelope of atmosphere is apt to be very tenuous, the possibility cannot be neglected that local atmospheres which exceed 10^{-12} terrestrial atmospheres may exist in the craters and depressions on the lunar surface.[4] These local atmospheres might consist of "pockets" of gas of somewhat greater density than that of the surrounding permanent atmosphere. This phenomenon could be caused to some extent by residual volcanic activity.[48, 103] Perhaps these local atmospheres could be generated and even maintained by this mechanism, thus assuming a more or less stable configuration. In conjunction with volcanic activity it may also be possible that local atmospheres are generated by processes such as the release of gases by cosmic-ray bombardment, vaporization of solid materials, radioactive decay of elements, and leakage of primeval gases trapped in rocks.[53, 65, 73] If these processes occur in areas of craters which are continually shielded from the sun's radiation, then the liberated gases may be cool enough to exist for long periods of time and again result in the establishment of permanent local atmospheres. Visual observations of the lunar surface tend to indicate that atmospheric pockets may be present.[103] They make their presence known by apparent visual surface changes but do not seem to be very stable since some of the observed changes have been reported to occur over a period of a few days. (For an impressive list of these reported observations, see Reference 103).

There does not appear to be any numerical estimates of the densities of these local atmospheres; thus, it may be concluded that although their existence is indicated to some extent, they are rather speculative. Therefore, as an upper limiting value of atmospheric density which may exist permanently, the value of 10^8 molecules per cc (arbitrarily 10 times Bobrovnikoff's estimate) can be chosen realizing that local variations of greater density in craters and depressions may exist. It is rather futile, however, to try to estimate the magnitudes of these variations.

If each of these molecules were singularly ionized, an electron density of 10^8 per cm^3 would result. However, this is not realistic in view of Elsmore's result of 10^4 per cm^3, i. e., the electron density is not greater than this amount. Evans[26] concurs with this figure but Wachholder and Fayer[92] are of the opinion that electron densities in the vicinity of the moon may reach the values 10^6 or 10^7 per cm^3. Most of the estimates available seem to be lower than the latter value; however, for purposes of radar propagation calculations, the figure of 10^7 electrons per cm^3 will be assumed and considered a liberal upper limit estimate. In view of the many lower estimates, this value may prevail only during periods of strong solar activity.

Having chosen upper limit values of molecular and electron densities (10^8 and 10^7 per cm^3, respectively) it is necessary to estimate the gas temperature. This is done by considering the extreme surface temperature variations which have been estimated for the night and day sides of the moon. These estimates are 90°K on the night side and 400°K on the day side.[1, 14, 50, 106] Of course, the gas temperature above the surface may be considerably greater than the surface temperature, e.g., the terrestrial exosphere has a temperature of about 1500°K.[52] However, for the assumed lunar atmosphere a very large variation in the upper limiting temperature can be tolerated without appreciably affecting the maximum electron collision frequency values to be expected. In this case, the maximum collision frequency values are determined by the low rather than the high temperatures. This is because the density of neutral molecules is less than 10^8 per cm^3 and, assuming space-charge neutrality of the lunar plasma, the collision frequency is determined primarily by electron-ion (coulomb) interaction. Therefore, it will be assumed that the lowest gas temperature likely to be encountered is that of the nighttime surface value, i.e., 90°K. If under this condition, the electrons tend to recombine with ions or become attached to neutral molecules, the ionic absorption of the plasma will be less than that which is calculated.

b. Estimation of Electron Collision Frequencies

In the calculation of ionic absorption of radar frequency waves in a plasma, it is the electrons rather than the ions which have the dominant role as current carriers, since the mobility of the electron is much greater due to their relatively small mass. The heavier ions and neutral molecules come into play primarily as collision partners. The electron collision frequency (ν) has a contribution from collisions with neutral molecules (ν_{en}), and a contribution from collisions with ions (ν_{ei}). The contribution due to electron-electron interaction is assumed to be negligible and space change neutrality is assumed to prevail.

To a first order of approximation, the collision frequency of electrons with neutral molecules is given by

$$\nu_{en} = \frac{4}{3} n_n (\pi\sigma^2) \left(\frac{8kT}{\pi m_e}\right)^{\frac{1}{2}} \quad 61^{*} \tag{1}$$

where

n_n = number density of neutral molecules
$(\pi\sigma^2)$ = kinetic cross section
k = Boltzmann's constant
m_e = electron mass
T = absolute temperature

Kinetic cross section is somewhat dependent upon temperature, usually tending to increase with decreasing temperature; however, it is still of the order of 10^{-16} cm^2 for most gases. For present purposes, it is sufficient to take

$$(\pi\sigma^2) \cong 4\pi \times 10^{-16} \text{ cm}^2,$$

so that expression (1) becomes

$$\nu_{en} \cong 10^{-9} n_n \sqrt{T} \tag{2}$$

where n and T have units of cm^{-3} and degrees K respectively, and T is understood to refer to the electrons and neutral molecules.

The collision frequency of electrons with positive ions is, to a first order of approximation, given by

$$\nu_{ei} = \frac{4}{3} \frac{\pi e^4 n_e}{\left(2\pi m_e k^3 T\right)^{\frac{1}{2}}} \log_e \left[1 + \left\{ \frac{4}{\sqrt{\pi} \; e^3 \sqrt{n_e}} \left(\frac{kT}{2}\right)^{\frac{3}{2}} \right\}^2 \right] \quad 61 \tag{3}$$

---

* Reference Number

where

e = electronic charge

n_e = number density of electrons (= density of positive ions),

and the Debye distance is taken to be the characteristic distance between neighboring particles (see Equation 17 of Reference 61). If the universal constants in expression (3) are inserted, the result is

$$\nu_{ei} \cong 1.82 \frac{n_e}{T^{\frac{3}{2}}} \log_e \left\{ 1.4 \times 10^8 \frac{T^3}{n_e} \right\} \quad (4)$$

where the units of n_e and T are cm^{-3} and degrees K respectively, and the temperature of electrons and ions are assumed equal.

The collision frequencies ν_{en} and ν_{ei} are plotted versus particle density for various temperatures in Figure IIIA-2. Inspection of the curves reveals that the contribution of neutral particles to the total collision frequency ($\nu = \nu_{en} + \nu_{ei}$) is negligible. Thus, it can be assumed that $\nu \cong \nu_{ei}$. It follows that the greatest value of ν is obtained for the lowest temperature which, in this analysis, is 90°K. This may be unrealistic if on the cold side of the moon (where this temperature supposedly prevails) the electrons undergo recombination and attachment to a considerable degree. This would lower the electron density and result in a lower collision frequency. The value of $\nu \cong \nu_{ei}$ from the curves for T = 90°K is (assuming an electron concentration of 10^7 per cm^3) approximately $3.4 \times 10^5 \ sec^{-1}$. This value will be used in estimating the ionic absorption of the lunar plasma realizing that the actual collision frequency could be much lower.

c. Estimation of Attenuation Due to Ionic Absorption

The degree of anisotropy of the lunar atmosphere is determined by the magnetic field that may be present. Some Russian estimates range from 50 to 100 gamma [92] (5×10^{-4} to 10^{-3} gauss.) (The terrestrial magnetic field varies between 0.6 and 0.3 gauss at the surface of the earth.) There does not seem to be definite evidence, however, that the moon possesses a permanent magnetic field. [38] According to Geer[35], the lunar magnetic field is probably not larger than a few thousand gamma. In view of certain studies (References 62 and 73) this last estimate seems excessively liberal; however, for the maximum effect of a magnetic field on radar propagation a value of 3000 gamma was assumed.

To calculate ionic absorption, the standard formula for the propagation constant will be used, i.e., if the waves propagate according to e^{ikx}, then k^2 is given by

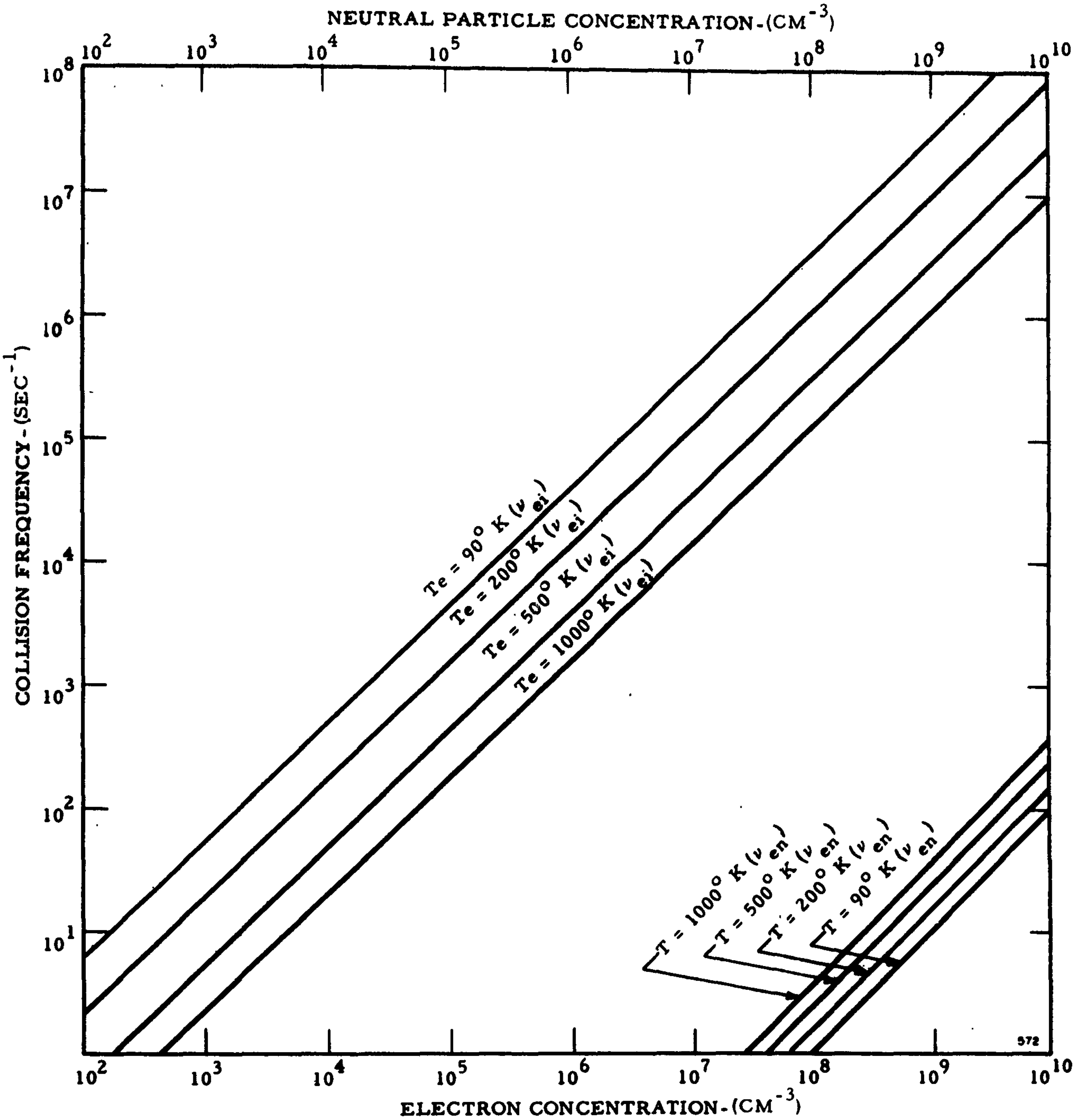


Figure III A-2. Electron Collision Frequency

$$k^2 = \left(\frac{\omega}{c}\right)^2 \left\{ 1 + \frac{1}{\alpha + i\beta + \left[-\gamma_T^2 \delta \pm \sqrt{\gamma_T^4 \delta^2 + \gamma_L^2} \right]} \right\}, \tag{5}$$

where

$$\alpha = -\left(\frac{\omega}{\omega_p}\right)^2, \beta = \left(\frac{\nu\omega}{\omega_p^2}\right), \quad \omega_p = \frac{n_e e^2}{\epsilon_o m_e}$$

$$\gamma_T = \gamma \sin\theta, \quad \gamma_L = \gamma \cos\theta, \quad \gamma = \frac{\omega_B \omega}{\omega_p^2}$$

$$\delta = \frac{1}{2}(1 + \alpha + i\beta)^{-1},$$

ω = radian frequency of impressed field, rad/sec

ω_p = plasma frequency, rad/sec

ω_B = electron gyro frequency $\left|\frac{eB}{m_e}\right|$, rad/sec

B = magnetic field strength - weber per meter in RMKS units

θ = angle between magnetic field and direction of propagation.

The plasma frequency is (for $n_e = 10^7$ electrons cm^{-3})

$\omega_p \cong 1.8 \times 10^8$ rad/sec ($\cong 29$ mc/s)

and the gyro frequency is (for 3000 γ)

$\omega_B \cong 0.6 \times 10^6$ rad/sec ($\lesssim 0.1$ mc/s).

The real part of k (Equation 5) is the phase constant in radians per unit length, and the imaginary part of k is the attenuation in nepers per unit length. These quantities depend upon θ (the direction of propagation with respect to the magnetic field) in a very complicated way. However, for $\omega >> \omega_B$, the term

$$-\gamma_T^2 \delta \pm \sqrt{\gamma_T^{\ 4} \delta^2 + \gamma_L^{\ 2}} \quad ,$$

in Equation (5) becomes quite small compared to $|\alpha + i\,\beta|$. Therefore, for the frequencies of interest (f > 100 mc/s), we can neglect this term without appreciable error, with the result that k^2 is given approximately by

$$k^2 \cong \left(\frac{\omega}{c}\right)^2 \left\{1 + \frac{1}{\alpha + i\beta}\right\}$$

$$\cong \left(\frac{\omega}{c}\right)^2 \left\{\left[1 - \frac{\omega_p^2}{\omega^2 + \nu^2}\right] - i\, \frac{\omega_p^2 \, \frac{\nu}{\omega}}{\nu^2 + \omega^2}\right\} \qquad (6)$$

Further, since the maximum estimated collision frequency is 3.4×10^5 sec^{-1}, then $\omega >> \nu$, and it follows that, without appreciable error,

$$R_e\,[k] \cong \frac{\omega}{c} \left\{1 - \frac{1}{2}\left(\frac{\omega_p}{\omega}\right)^2\right\} \text{ radians/meter} \qquad (7a)$$

$$I_m\,[k] \cong \frac{\omega}{c} \left\{\frac{1}{2} \; \frac{\frac{\nu}{\omega}\left(\frac{\omega_p}{\omega}\right)^2}{1 - \frac{1}{2}\left(\frac{\omega_p}{\omega}\right)^2}\right\} \text{ nepers/meter} \qquad (7b)$$

The quantity $I_m[k]$ is plotted in Figure IIIA-3 in units of db per kilometer and the phase constant is plotted in units of radians per kilometer. It is evident from expression (7a) that the phase constant will differ from its free space value by less than about 0.08 per cent for frequencies above 1 kmc; the attenuation due to ionic absorption decreases with increasing frequency as $\left(\frac{1}{\omega}\right)^2$, being less than 0.1 db per kilometer for frequencies above a few hundred megacycles.

d. Estimation of Attenuation Due to Molecular Resonant Absorption

Besides ionic absorption of the lunar plasma in the microwave spectrum, it is possible that sufficient quantities of atmospheric gases are present to give appreciable absorption due to molecular rotation (resonant absorption). In order to estimate this quantity, it is necessary to know the types and relative amounts of constituent gases likely to be present. However, at present these questions cannot be answered. The best that can be done in this respect is to consider the effects (insofar as possible) of the gases which some researchers postulate to be present in the lunar atmosphere. These gases include, (see References 48 and 73):

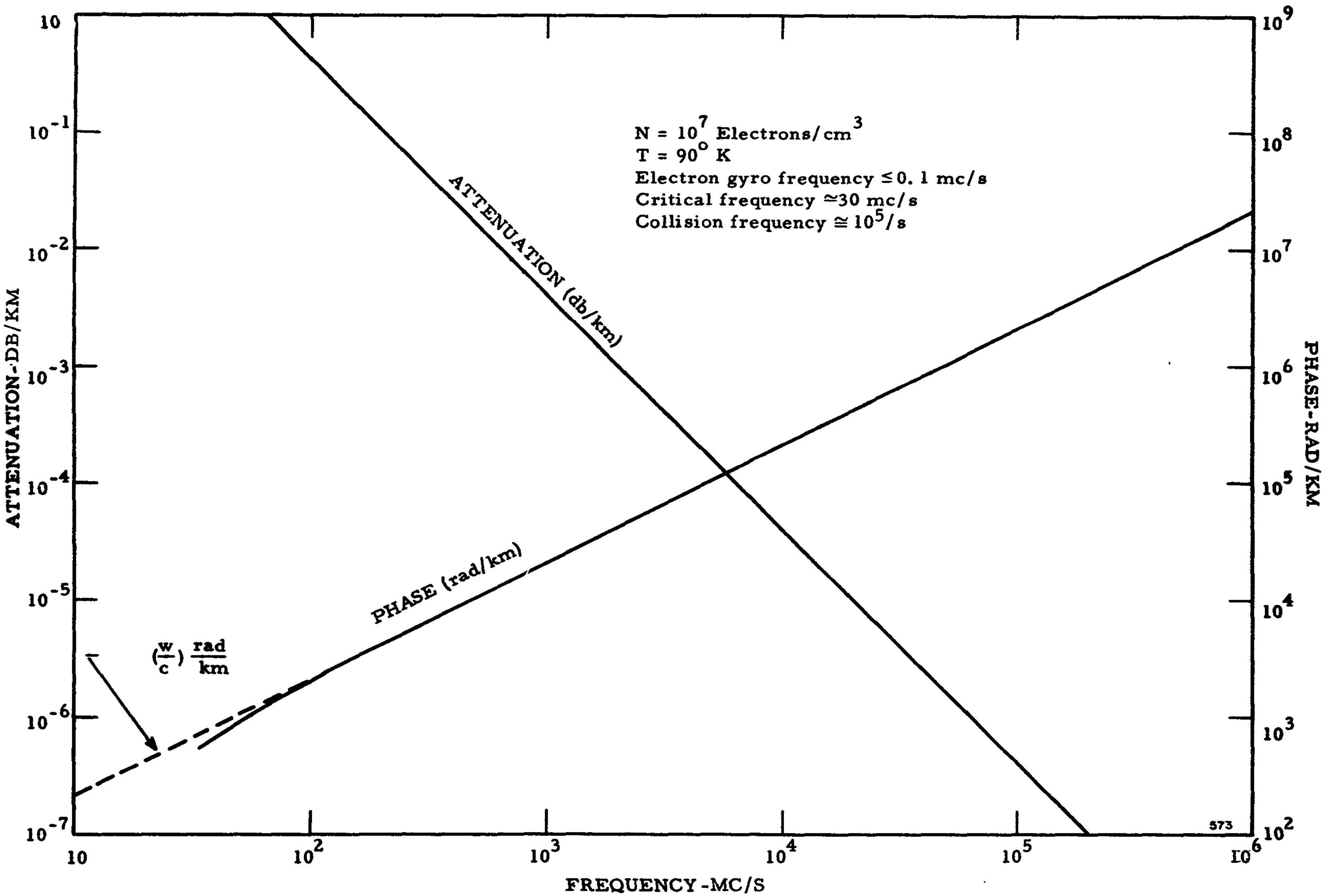


Figure IIIA-3. Ionic Absorption

Radon
Krypton
Xenon
Argon
Neon
Helium
Water Vapor
Mercury Vapor
Sulfur Dioxide
Carbon Dioxide

The absorption spectra of the inert gases radon, krypton, xenon, argon, neon and helium, and also mercury vapor are very weak in the microwave spectrum; their effect is expected to be appreciable only in the ultra-violet range and beyond.[111] Therefore, they are not considered here. This leaves only water vapor, sulfur dioxide, and carbon dioxide as possible absorbers at radar frequencies. Calculated data are available on water vapor and sulfur dioxide in Reference 36.*

In Reference 36, the absorption coefficients are calculated for the conditions T = 300°K, P (pressure) = 1 mm Hg and the half widths of the absorption lines are assumed to be (at half maximum intensity) 14 mc/s for water vapor, and 25 mc/s for sulfur dioxide. In order to adjust these data to lunar atmospheric conditions, the following procedure has been employed.

At resonance, the peak absorption is given approximately by the expression[85]

$$\gamma_{max} = \frac{4\pi^2 h N f_v \mu^2 \nu_o^3}{3c(kT)^2 \Delta\nu} \text{ nepers/cm} \tag{8}$$

where

h = Planck's constant = 6.624×10^{-27} erg-second
N = molecular density, cm^{-3}

* Presently, no data has been obtained for carbon dioxide absorption of microwave frequencies.

f_v = fractional number of molecules in a particular vibrational state

μ = molecular dipole moment in Debye units, or 10^{-18} esu

c = speed of light in vacuum = 3×10^{10} cm/second

k = Boltzmann's constant = 1.38×10^{-16} erg/°K

T = absolute temperature, degrees K.

ν_o = center frequency of absorption line, cycles per second, and

$\Delta\nu$ = line breadth parameter in cycles per second

Equation (8) suggests that γ_{max} for various conditions can be estimated, i.e., various values of T, $\Delta\nu$ and N if calculated values of γ_{max} are available for some fixed conditions. For example, let the left-hand side of Equation (8) be known and denoted by γ_o for conditions T_o, $(\Delta\nu)_o$ and N_o. Then to a certain degree of approximation it can be assumed that γ_{max} (denoted by γ_1) for some other conditions, T_1, $(\Delta\nu)_1$ and N_1 is given by

$$\gamma_1 = \left[\frac{N_1}{T_1^2 (\Delta\nu)_1}\right] \left[\frac{T_o^2 (\Delta\nu)_o}{N_o} \quad \gamma_o\right] \tag{9}$$

Since the fixed conditions for the tabulated values of γ_o are known, i.e., $T_o = 300^\circ$K, $N_o = 3.22\times10^{16}$ molecules per cm^3 (this corresponds to 1 mm H_g pressure), $(\Delta\nu)_o$ = 14 mc/s and 25 mc/s for water vapor and sulfur dioxide, respectively, then it remains to choose values for N_1, T_1, and $(\Delta\nu)_1$ corresponding to lunar atmospheric conditions.

The relative amounts of the gases, water vapor and sulfur dioxide, which are likely to be present in the lunar atmosphere are not known. Thus, it will be assumed that $N_1 = 10^8$ molecules per cm^3; this will provide a maximum absorption since it corresponds to the assumption that all of the atmosphere is water vapor or it is all sulfur dioxide. T_1 will be taken as 273°K. This is an arbitrary choice, however, for uniformity the present calculations are based on a temperature $T_1 = 273^\circ$K for both gases. The lunar atmospheric pressure is extremely low, i.e., at 273°K,

$$P = NkT = (10^8 \text{ cm}^{-3})(1.38\times10^{-16} \frac{\text{erg}}{^\circ\text{K}})(273^\circ\text{K})$$

$$\cong 2.8\times10^{-9} \text{ mm } H_g.;$$

at 1000°K

$$P \cong 10^{-8} \text{ mm } H_g.$$

At this low pressure water vapor and sulfur dioxide may exist in the gaseous state at temperatures well below 273°K. This can be taken into account by multiplying the calculated values corresponding to 273°K by an appropriate factor.

Because the pressure is extremely low, the line breadth parameter $(\Delta\nu)_1$ is assumed to be due only to Doppler broadening since pressure broadening is expected to be negligible. The line breadth parameter in this instance is given by [35]

$$(\Delta\ \nu)_1 = 3.6\text{x}10^{-7} \sqrt{\frac{T}{M}}\ \nu_o, \text{ cps} \tag{10}$$

where M is the molecular weight of the gas. Equation (9) can now be rewritten (inserting the values of T_o, N_o, $(\Delta\nu)_o$, N_1, T_1 and $(\Delta\nu)_1$) as

$$\gamma_1 = \left[\frac{10^8}{(273)^2(3.6\text{x}10^{-7}\sqrt{\frac{273}{M}})\nu_o}\right] \cdot \left[\frac{(300)^2(\Delta\nu_o)}{3.22\text{x}10^{16}}\ \gamma_o\right], \text{ nepers/cm,}$$

$$= 6.31\text{x}10^{-2}\sqrt{M}\ (\frac{\Delta\nu_o}{\nu_o})\ \gamma_o\ ;$$

for water vapor M = 18, $\Delta\nu_o$ = 14 mc/s,
and

$$\gamma_{1_{H_2O}} \cong 3.3\text{x}10^{10}\ (\frac{\gamma_o}{\nu_o})_{H_2O}, \text{ db/km;} \tag{11a}$$

for sulfur dioxide, M = 64, $(\Delta\nu)_o$ = 25 mc/s,

and

$$\gamma_{1_{SO_2}} \cong 1.1\text{x}10^{11}\ (\frac{\gamma_o}{\nu_o})_{SO_2}, \text{ db/km,} \tag{11b}$$

where γ is the absorption coefficient in units of nepers per cm at the frequency ν_o in cycles per second. Thus, for example, the first absorption line for water vapor tabulated in Reference 36 occurs at approximately 23,400 mc/s and the corresponding absorption coefficient is $9.0\text{x}10^{-5}$ nepers per cm. For the assumed lunar conditions Equation (11a) gives

$$(\gamma_1)_{H_2O}\Big|_{\nu_o \cong 23,400 \text{ mc/s}} \cong (3.3\text{x}10^{10})(\frac{9\text{x}10^{-5}}{23,400\text{x}10^6})$$

$$\cong 1.3\text{x}10^{-4}, \text{ db/km,}$$

which serves to illustrate the procedure for calculating the envelopes of absorption in Figure IIIA-4.

The graphs of Figure IIIA-4 were constructed by making "spot" calculations, using Equations (11a) and (11b), of the more intense spectral lines of water vapor and sulfur dioxide. This means that for a given resonant frequency the absorption coefficient at that frequency will fall on or below the curve of Figure IIIA-4 for that particular gas.

These curves may be somewhat misleading at first inspection since they tend to give the impression that there is a continuous band of absorbing frequencies. This is not the case. For the water vapor absorption lines, the first two (at the lower frequencies) tabulated in Reference 36 are clearly labeled in Figure IIIA-4. These are the lines 23,382.5 mc/s and 184,362.2 mc/s, which are rather widely spaced. Their full widths may be calculated from Equation (10); these widths are 0.066 mc/s at ν_o = 23,382.5 mc/s and 0.51 mc/s at 184,362.2 mc/s. These widths are extremely small compared to their center frequencies. The remaining lines tabulated in Reference 36, of which there are 586, lie in the frequency interval 323,158.5 mc/s to 29,502,455.0 mc/s. Since there are so many of these lines, only the maximum absorption envelope has been plotted in Figure IIIA-4. The average density of lines in this interval is given approximately by 2×10^{-5} lines/mc/s, and the average full width of these lines can be estimated by taking the average widths of highest and lowest frequency lines in this interval. Thus, at 323,158.5 mc/s the full width is 0.90 mc/s and at 29,502,455.0 mc/s the full width is 83 mc/s, so that the average width is approximately 42 mc/s. Since there are 586 lines, then

$(586)(42) = 2.46\times10^4$ mc/s gives the total frequency band for which absorption is appreciable. Finally, the bandwidth of the interval in question is 29,502,455.0 mc/s minus 323,158.5 mc/s, or, 29,179,296.5 mc/s, so that the percentage of this total band width over which absorption is expected to be appreciable is only about

$$\left(\frac{2.46\times10^4}{29,179,296.5}\right) = 8.4\%$$

For sulfur dioxide, the first line tabulated in Reference 36 occurs at 677.82 mc/s; the remaining lines occur in the interval 12,258.17 mc/s to 1,339,383.13 mc/s, there being 202 lines in this interval. The average line density in this interval is approximately 1.52×10^{-4} lines/mc/s. The average full width of the lines is approximately 1 mc/s, so that the percentage of the total bandwidth over which absorption is expected to be appreciable is approximately 0.015 per cent.

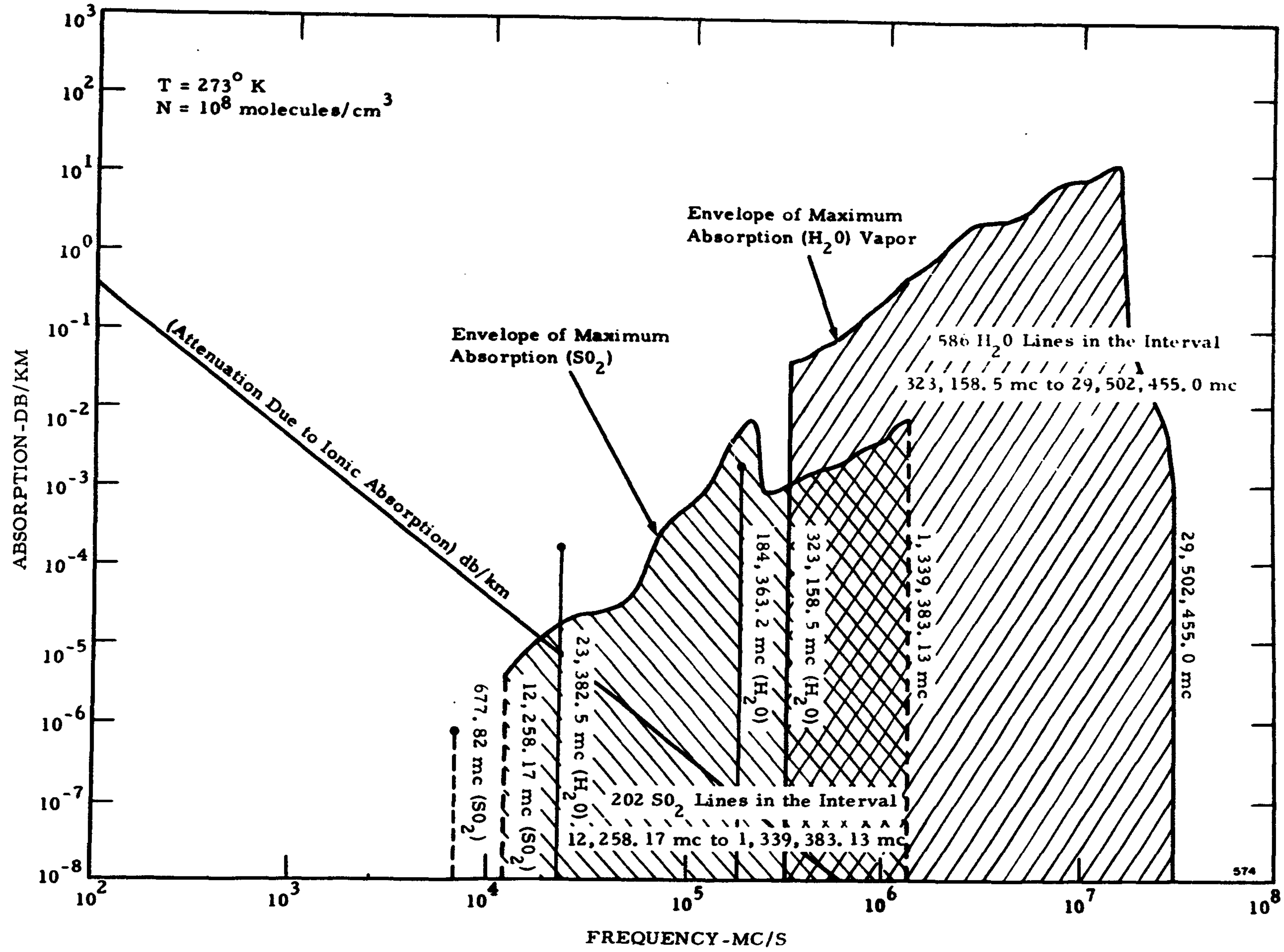


Figure IIIA-4. Molecular Resonant Absorption

The curves of Figure IIIA-4 can be adjusted for a change in temperature by multiplying the ordinates by the appropriate factor. From Equations (9) and (10) it is evident that the maximum absorption at resonance varies as $T^{-5/2}$. Thus, for a temperature of 200°K, the ordinates of Figure IIIA-4 should be multiplied by the factor

$$\left(\frac{273}{200}\right)^{5/2} \cong 2.17$$

This increases the absorption; however, it also decreases the line width (see Equation 10). Since the line widths are extremely narrow even at 273°K, it is expected that lowering the temperature will not noticeably change the situation, for if resonant absorption of radar waves is negligible (due to the narrowness of the absorption lines) at 273°K, then it is also negligible at lower temperatures. Further, it has been necessary to assume that the entire lunar atmosphere is composed of either water vapor or sulfur dioxide. If this is not the case, i.e., if the quantities of these gases make up only a fractional part of the atmosphere, then the absorption coefficients will be lowered by a factor corresponding to the fractional amounts. (The absorption is proportional to the number density of the absorbing particles).

The attenuation due to ionic absorption of Figure IIIA-3 has been sketched on the graph of Figure IIIA-4 for purposes of comparison. The comparison indicates that at frequencies somewhat above 10 kmc/s molecular resonant absorption is expected to be the dominant factor in the attenuation of radar waves. Again, it must be recalled that maximum molecular densities (10^8 cm^{-3}) were used in calculating the resonant absorption curves and for this reason the absorption may be too high. Even more important, however, is the narrowness of the line widths. As already mentioned, the line widths are so small that the attenuation due to molecular resonant absorption may be completely negligible compared to that due to ionic absorption.

The attenuation due to nonresonant absorption of the lunar atmosphere will be negligible compared to ionic and molecular resonant absorption under the assumed conditions.

e. Dust Clouds

In the event that clouds of dust may appear from time to time due to volcanic activity, meteor impact, or other phenomena, these clouds would represent changes in refractive index and affect radar propagation to some extent. One possible effect is reflections from these clouds. From an elementary viewpoint, the degree of this effect depends primarily upon the mass concentration of the cloud and upon the refractive index of the dust material. The mass concentration or quantity of mass per unit volume of a "typical cloud" cannot be estimated. If a mass concentration is assumed and dielectric constants of some materials likely to be present on the lunar surface considered, an estimate of reflections can be obtained.

The type of material which makes up the lunar surface is not definitely known. Some of the substances which are thought to have a fairly high probability of occurrence are given in Reference 11. Of these substances, the one having the highest dielectric constant is basalt; depending upon composition, its dielectric constant ranges from 5 ϵ_0 to somewhat less than $30\epsilon_0$.* (Density varies from approximately two to three grams per cm^3.)

An expression which is applicable for the refractive index changes due to the presence of aerosols is[18]

$$N = 1.5 \left(\frac{n_1^2 - 1}{n_1^2 + 2} \right) \frac{c}{\rho} \qquad (12)$$

where N is the difference between the refractive index of the aerosol and that of the medium, expressed in N units. In this case, the medium is the lunar atmosphere (or $N = \Delta n \times 10^6$), c is the mass concentration of the suspension in μ gm/cm^3, n_1 is the refractive index of the suspended substance, and ρ is the mass density of the suspended substance in gm/cm^3.

At radar frequencies above a few kilomegacycles per second, it is expected that the dielectric constants of these substances will differ from the optical values by a small amount. Since the optical value is in the approximate range 1 to 10 ϵ_0 (this is the case for most known minerals**) and since frequencies greater than 100 mc are to be considered, the effective dielectric constant may be somewhat greater than optical values, but will probably be less than 30 ϵ_0. Thus, it was assumed that some typical values of dielectric constant for lunar materials at radar frequencies would be 1.5, 3, 5, and 10 ϵ_0. Since the mass density of a typical substance is in the range 2 to 3 gm/cm^3, an average value would be approximately 2.5 gm/cm^3. If these values are substituted into Equation (12) the results are

* These are low frequency (1000 cps) values obtained from Reference 11.
** See, for example, Reference 49.

$$\epsilon_1 = 1.5\,\epsilon_o \qquad n_1^2 = 1.5 \qquad N = 0.086c$$

$$\epsilon_1 = 3\,\epsilon_o \qquad n_1^2 = 3 \qquad N = 0.24c$$

$$\epsilon_1 = 5\,\epsilon_o \qquad n_1^2 = 5 \qquad N = 0.40c$$

$$\epsilon_1 = 10\,\epsilon_o \qquad n_1^2 = 10 \qquad N = 0.45c$$

These curves are plotted in Figure IIIA-5.

It should be noted that Equation (12) is independent of particle size, however, the validity of this formula for a wide range of particle sizes is uncertain. Good experimental agreement is obtained for particles ranging from a fraction of a micron to a few microns in size, substance densities ranging from 1.032 to 7.81 gm/cm^3, refractive indices ranging from 1.486 to infinity, and for mass concentrations ranging from 2 to 50 micrograms per cm^3.[18] It appears that the formula is applicable here if the dust particle sizes do not lie too far out of the range indicated above. It might also give good agreement for particle sizes which are less than a wave length but greater than a few microns.

A "typical" lunar dust cloud may not be confined enough (due to low gravitational attraction and vacuum conditions) to yield an appreciable change in refractive index over a distance less than a radar wavelength (which is normally required for good reflection). Nevertheless, there may be some value in attempting to estimate a reflection coefficient which will give a measure (although somewhat crude) of radar reflections to be expected. To do this the reflection coefficient is taken at normal incidence for a plane wave entering medium D (the dust cloud) from medium A (the lunar atmosphere). The reflection coefficient (radio of incident electric intensity to reflected electric intensity) is given by

$$|\rho| = \left| \frac{\sqrt{\epsilon_A} - \sqrt{\epsilon_D}}{\sqrt{\epsilon_A} + \sqrt{\epsilon_D}} \right| = \left| \frac{n_A - n_D}{n_A + n_D} \right|^{68} \tag{13}$$

where ϵ_D, ϵ_A, n_D, and n_A are the dielectric constants and refractive indices respectively, of media D and A. N of Equation (12) is, in terms of n_D and n_A,

$$n_D - n_A = N\text{x}10^{-6},$$

so that

$$\rho = \frac{N\text{x}10^{-6}}{2n_A + N\text{x}10^{-6}}, \quad n_A = \frac{\epsilon_A}{\epsilon_o} \tag{14}$$

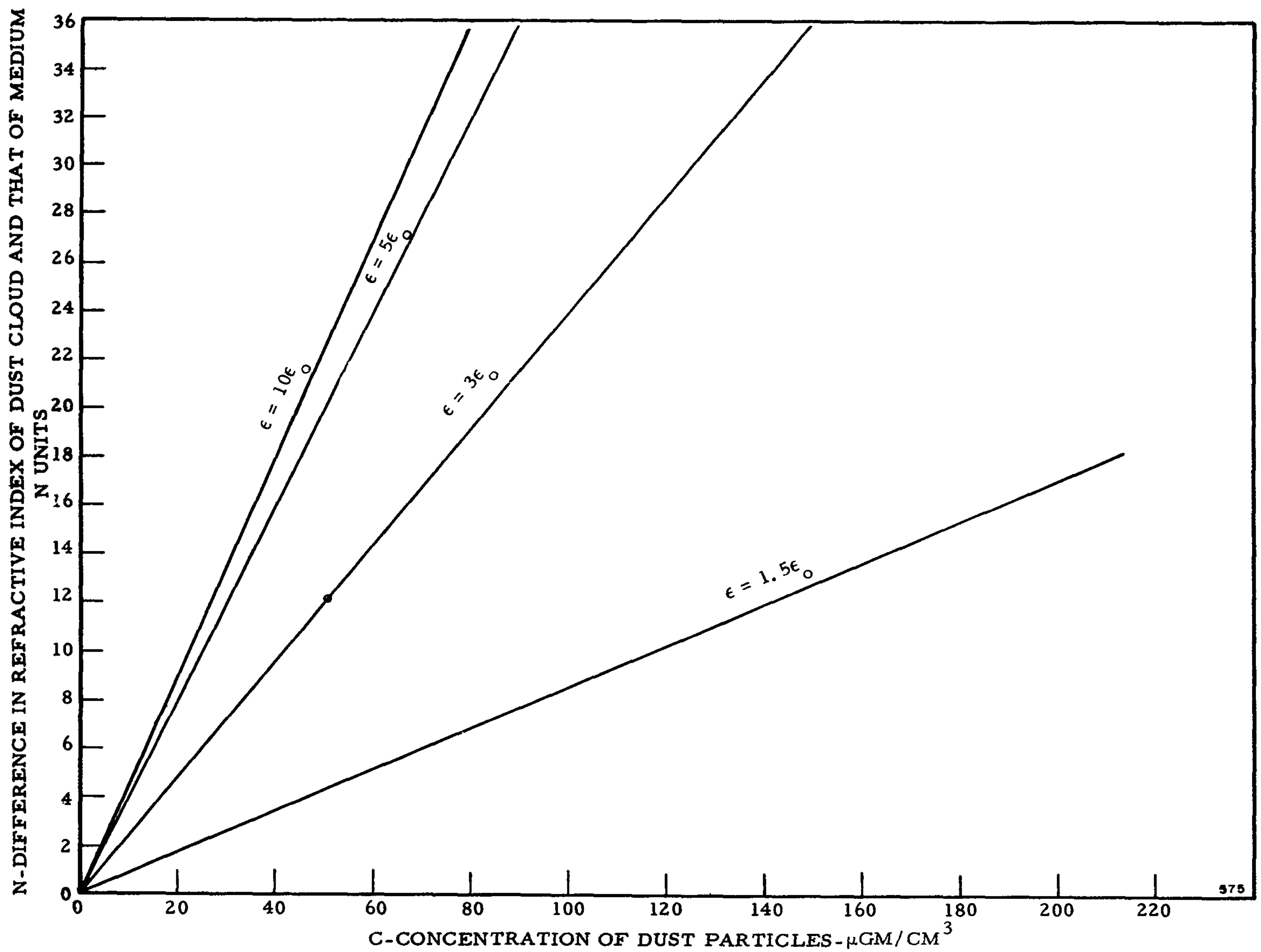


Figure IIIA-5. Dust Concentrations vs. Refractive Indices where ϵ_o is the free-space dielectric constant. Thus, knowing the mass concentration, C, of the dust cloud and the refractive index of the lunar atmosphere, Equations (12) and (14) can be used to estimate the reflection coefficient. For $n_A \cong 1$, it is justified to assume, since the lunar atmosphere is extremely rarefied, that

$$|\rho| \cong \frac{N}{2} \times 10^{-6} \quad , \quad n_A >> N \times 10^{-6} \quad , \text{ from Equation (14)}$$

so that $|\rho|$ is likely to be very small for variations in N of a few N-units, i.e., $N \times 10^{-6} << 1$.

Another effect of density contrasts in radar propagation is bending of the rays as they pass from medium A to medium D.

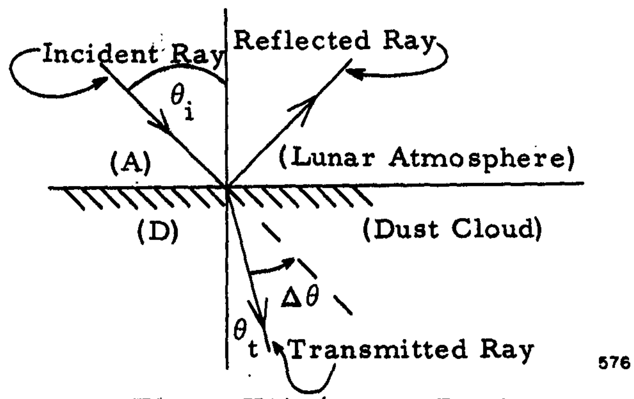


Figure IIIA-6. Ray Bending

The relationship between the incident ray direction and the transmitted ray direction (see Figure IIIA-6) is

$$\frac{\sin \theta_t}{\sin \theta_i} = \sqrt{\frac{\epsilon_A}{\epsilon_D}} = \frac{n_A}{n_D} \tag{15}$$

where it is assumed that the dust cloud has a uniform density and its edge can be treated as an interface between media A and D. Since $n_D - n_A = N \times 10^{-6}$, then

$$\frac{n_A}{n_D} = 1 - \frac{N}{n_A} \times 10^{-6} \quad ,$$

and Equation (15) becomes

$$\frac{\sin \theta_t}{\sin \theta_i} = 1 - \frac{N}{n_A} \times 10^{-6} \tag{16}$$

It is expected that $n_D >> N \times 10^{-6}$ so that by setting $\theta_t = \theta_i - \Delta\theta$, Equation (16) is approximated by

$$\Delta \theta \cong (\tan \theta_i) \frac{N}{n_A} \times 10^{-6}, \text{ for a small } \Delta\theta, \tag{17}$$

i.e., for $\Delta\theta \cong \sin \Delta \theta$.

Although we cannot estimate the mass concentration of a typical lunar dust cloud, it is interesting to assume a value of C (mass concentration) and calculate the reflection coefficient from Equation (14) and the change in ray angle from Equation (17). Thus, it is assumed that, for purposes of calculation, $C = 50\ \mu\ gm/cm^3$. (If the particles are spheres nominally 10 microns in diameter and the mass density is $2.5\ gm/cm^3$ this gives a number concentration of approximately 5×10^4 dust particles per cm^3). If a dielectric constant for the dust material of $3\ \epsilon_o$ is assumed then the graph in Figure IIIA-5 gives an N value of 12 for $C = 50\ \mu\ gm/cm^3$. Since it is expected that n_A (the refractive index of the lunar atmosphere) will be such that $n_A \cong 1$, then Equation (14) gives

$$\left| \rho \right|_{\substack{\epsilon_1 = 3\epsilon_o \\ C = 50\ \mu\ gm/cm^3}} \cong 6 \times 10^{-6} \tag{18a}$$

and Equation (17) gives

$$\Delta \theta \Big|_{\substack{\epsilon_1 = 3\epsilon_o \\ C = 50\ \mu\ gm/cm^3}} \cong 12 \times 10^{-6} \tan \theta_i \text{ radians} \tag{18b}$$

These results are not particularly meaningful except that they indicate the order of magnitude of the effect of dust clouds on the reflection coefficient at normal incidence and the amount of bending at a plane interface. Inspection of Equations (14) and (17) reveal that both of these quantities are directly proportional to the mass concentrations of the dust clouds and are more or less independent of dust particle size for wavelengths much greater than the particle size.

The presence of dust clouds can also have the effect of attenuating radar waves by means of scattering and absorption. Again, the magnitude of this effect depends upon the dust cloud densities, for which estimates are not available.

This type of problem is usually approached by assuming that the scattering particles are imperfect dielectric (having ohmic loss) spheres.

The values of the complex dielectric constant at the frequencies for which calculations are to be made must be known. Finally, the dust particle size must be known, because the wavelength to particle diameter ratio is a critical parameter if this ratio should prove to be near unity. Thus, not only must the cloud densities be known, but particle sizes and the complex dielectric constant of the scattering particles must also be known. This problem is much more complicated than estimated refractive index changes considered in previous paragraphs.

The estimation of a "typical" complex dielectric constant must be somewhat arbitrary. The tables of Reference 11 were scanned in an effort to choose this parameter. This reference has tables of approximately 35 minerals and their electrical properties which are thought to be representative of lunar surface materials. The tabulated complex dielectric constants have a wide range of values, e.g., Quartz $\epsilon_o = 4.84\, \epsilon_o\, (1 - j\, 0.008)$ farad/m at 1000 cps, and Basalt (New Jersey) $\epsilon_o = 26.7\, \epsilon_o\, (1 - j\, 0.444)$ farad/m at 1000 cps. A choice of $\epsilon_o = 26.7\, \epsilon_o\, (1 - j\, 0.444)$ was made for purposes of calculation because it has the highest loss tangent (0.444) of all the values tabulated. This gives the highest ohmic loss in the scattering particles and, therefore, the greatest attenuation. Thus, if the lunar materials have loss tangents less than 0.444 at 1000 cps, then the calculated attenuation will be higher than the actual case. If there are lunar materials which have loss tangents greater than this value, the calculated attenuation will obviously be too low.

The authors of Reference 11 have analyzed radio and optical data of the lunar surface and concluded that the range of particle size likely to prevail on the moon is probably 10 to 300 microns. In Reference 106 the lower end of the estimated range extends to 1 micron. On the basis of these estimates, calculations were made for particle sizes of 1, 10, and 100 microns to determine the maximum attenuation and variation of attenuation with particle size.

Attenuation is calculated using the following formula from Reference 54:

$$\frac{\gamma}{n} = 434 \left(\frac{\lambda^2}{2\pi}\right) \left(\frac{2\pi a}{\lambda}\right)^3 \left[c_1 + c_2 \left(\frac{2\pi a}{\lambda}\right)^2 + c_3 \left(\frac{2\pi a}{\lambda}\right)^3\right], \quad \rho << 1 \qquad (19)$$

where

$\rho = \dfrac{2\pi a}{\lambda}$,

a = radius of scattering particle, cm

λ = free space wavelength of incident radiation, cm

γ = attenuation, db/km

n = scattering particle concentration, m^{-3}, and the coefficients c_1, c_2, and c_3 are given by

$$c_1 = \frac{6\epsilon_2}{(\epsilon_1 + 2)^2 + \epsilon_2^2}, \tag{20a}$$

$$c_2 = \frac{\epsilon_2}{15}\left\{\frac{3(7\epsilon_1^2 + 4\epsilon_1 - 20 + 7\epsilon_2^2)}{\left[(\epsilon_1 + 2)^2 + \epsilon_2^2\right]^2} + \frac{25}{(2\epsilon_1 + 3)^2 + 4\epsilon_2^2} + 1\right\}, \tag{20b}$$

$$c_3 = \frac{4}{3}\ \frac{(\epsilon_1 - 1)^2(\epsilon_1 + 2)^2 + \epsilon_2^2\left[2(\epsilon_1 - 1)(\epsilon_1 + 2) - 9\right] + \epsilon_2^4}{\left[(\epsilon_1 + 2)^2 + \epsilon_2^2\right]^2}, \tag{20c}$$

where the complex dielectric constant ϵ_c is given by

$$\epsilon_c = \epsilon_1 - i\,\epsilon_2, \text{ (dimensionless)} \tag{20d}$$

and is the value relative to free space. The choice of a complex dielectric constant from Reference 11 corresponds to

$$\epsilon_1 = 26.7 \text{ at } 1000 \text{ cps}$$
$$\epsilon_2 = 0.444\,(26.7) = 11.85 \text{ at } 1000 \text{ cps.}$$

The dimensionless complex dielectric constant can be written as

$$\epsilon_c = \epsilon_r\left(1 - j\frac{\sigma}{\omega\epsilon_o\epsilon_r}\right) \tag{21}$$

where σ is the conductivity, ω is the impressed radiation frequency, and ϵ_r is the relative (real) dielectric constant as compared to the free space value of unity. As the frequency increases, ϵ_r will tend toward its optical value. However, to simplify calculations it will be assumed that ϵ_r remains constant for all frequencies and may be given by its low frequency value of 26.7. This assumption will not significantly affect the results in present context.

The attenuation per unit particle density is plotted in Figure IIIA-7 with dust particle diameter as a parameter. Evidently, if the particle diameter is increased by a factor of 10, the attenuation (for the same particle concentration) is increased by a factor of 10^3. The formula of Equation (19) is not valid for $\left(\frac{2\pi a}{\lambda}\right) \geq 0.1$; therefore, the attenuation does not continue to increase indefinitely for high frequencies as the curves of Figure IIIA-7 imply. The value at which $\frac{2\pi a}{\lambda} = 0.1$ is indicated on each curve.

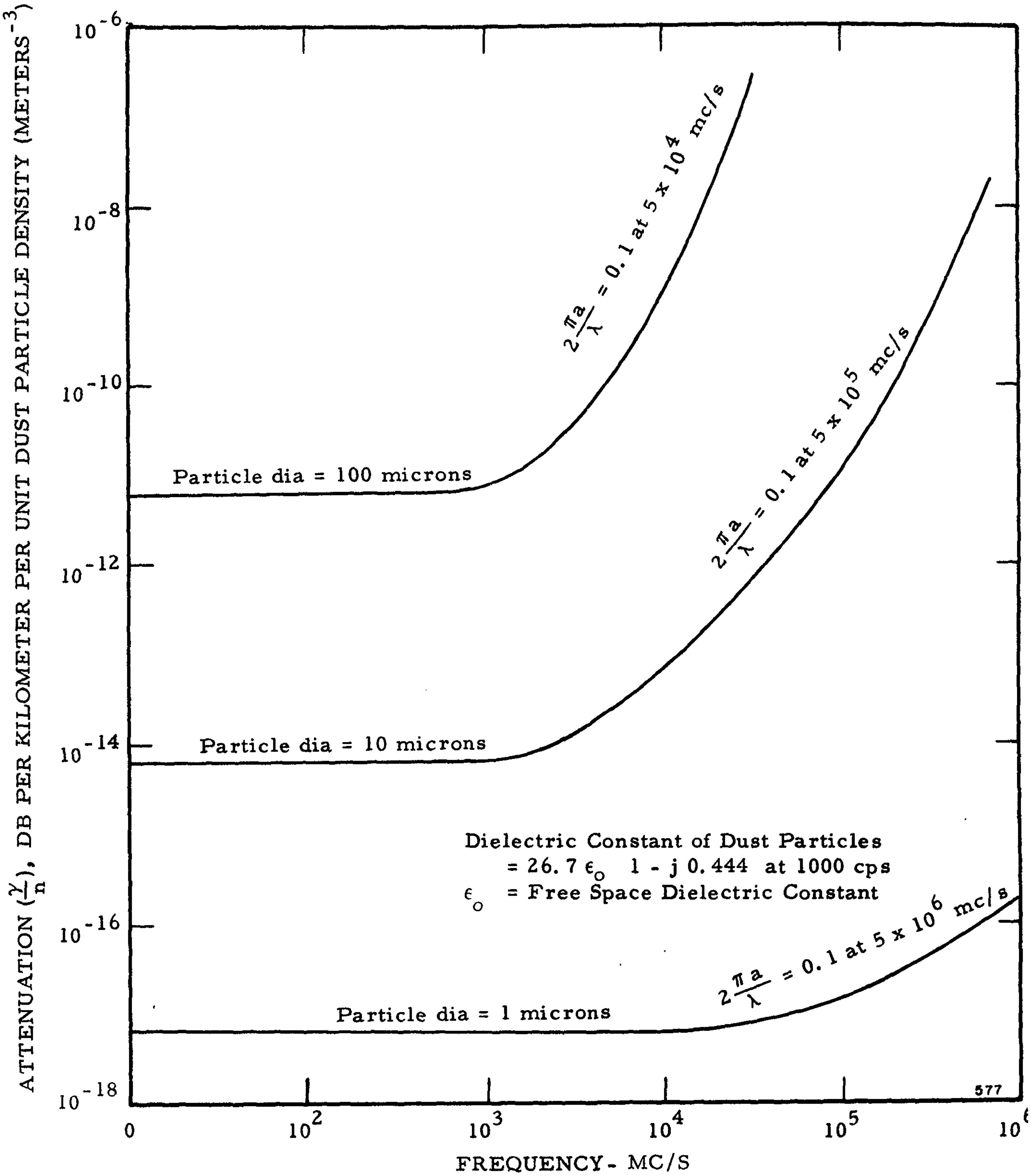


Figure IIIA-7. Aerosol Absorption (Dust)

By way of summary of this section it can be stated that the quantitative effects of dust clouds on radar propagation in the lunar atmosphere must remain indefinite until it is possible to make reasonable estimates of dust particle concentrations. What constitutes a reasonable estimate will depend upon the particular set of conditions. However, for a given set of conditions (i.e., known dust concentration, particle size, etc.) a prediction can be made as to the amount of reflection, ray bending and attenuation that is likely to prevail.

3. Estimation of the Various Propagation Effects

a. Attenuation

Neglecting for the moment the variations in the strength of the wave associated with the convergence or divergence of the ray paths, a wave is attenuated due to absorption and scattering by the various constituents of the medium. For purposes of this investigation these influences can be taken to be basically independent and additive. That is, attenuations of gas, free electrons and dust are estimated separately and then added together. The attenuation due to free electrons is dependent upon the density of neutral molecules and ions, because collisions play a critical role. The absorption by one type of gas molecule, however, will be essentially independent of the other concentrations since at the pressures expected, doppler effect (as opposed to pressure) is visualized as the dominant contributor to line broadening.

For a rather extreme choice of lunar atmospheric properties, except possibly local atmospheres, the estimated attenuation due to the free electron concentration is plotted versus frequency in Figure IIIA-3. The attenuation varies inversely as the square of the frequency and has a value near 0.005 db/km at 1.0 kmc/s.

Figure IIIA-4 indicates that molecular absorption will not be significant except possibly at resonant lines for water vapor in the frequency range above 300 kmc/s. Recalling that the values indicated in this figure are based on a molecule density of 10^8 cm^{-3} (corresponding to all the molecules in a maximum density situation being water vapor molecules) and that the resonant absorption lines are very narrow (occupying a small fraction of the frequency interval), the case for which molecular absorption would be important is extreme.

Attenuation values for New Jersey basalt dust particles having diameters of 1, 10 and 100 microns are plotted in Figure IIIA-7. Most types of lunar dust would be expected to have values well below those shown. An estimate of reasonable particle densities has not been ascertained, but only dense dust storms would be expected to create severe attenuation.

The general conclusion is that the normal lunar atmosphere would not significantly attenuate radar waves except possibly below 700 mc/s if assumed plasma conditions exist. This conclusion might not be justified in local atmospheres or dust clouds for which density estimates have not been attempted.

b. Refraction

The basic formula governing the path taken by a ray can be expressed as [54]

$$\vec{C} = \frac{1}{n} \vec{p} \times \vec{\nabla} n$$

in which $\vec{C}$ is the vector curvature, n is the refractive index and $\vec{p}$ is a unit vector in the ray direction (direction of propagation). Here the refractive index is taken to be real. If a complex refractive index is considered, the n in this section should be taken as the real part. The curvature of a line is defined as the reciprocal of the radius of curvature and becomes a vector when associated with the axis of rotation, the right-hand rule giving the sense. Anticipating cases for which the refractive index differs only slightly from unity, the 1/n factor shall be omitted.

Restricting our attention to cases for which the ray deviates only slightly from a straight path, $\vec{p}$ may be taken to be constant. Then the total bending of the ray between ℓ (distance along the path) = 0 and r is

$$\vec{\theta} = \int_0^r \vec{C}\, d\ell = \int_0^r (\vec{p} \times \vec{\nabla} n)\, d\ell$$

and the lateral deviation of the ray from the straight path at ℓ = R is

$$\vec{D} = \left(\int_0^R \vec{\theta}\, dr \right) \times \vec{p} = \int_0^R \int_0^r (\vec{p} \times \vec{\nabla} n \times \vec{p})\, d\ell\, dr = \int_0^R \int_0^r \vec{\nabla} n_{\perp}\, d\ell\, dr$$

in which $\vec{\nabla} n_{\perp}$ is the portion of $\vec{\nabla} n$ perpendicular to the ray path.

For the case in which $\vec{\nabla} n$ is constant along the path then

$$\vec{\theta} = (\vec{p} \times \vec{\nabla} n)\, R \text{ and}$$

$$\vec{D} = \vec{\nabla} n_{\perp}\, R^2/2.$$

Note that appreciable refraction results for reasonable values of ∇n only if the ray path remains in the region of the gradient for a considerable distance. This seems likely only for horizontal stratification and nearly horizontal rays.

The problem remains of estimating extreme values of the gradient of refractive index for the lunar atmosphere. Since the density of the normal lunar atmosphere appears to be at least a factor of 10^{-11} less than on the earth and the earth's total refractive index variation occurs in ranges of 10^{-4}, the net deviation of the lunar atmospheric refractive index from unity due to neutral gas molecules would not be expected to exceed 10^{-13}. If this is true, density contrasts could not cause significant refractive index gradients.

For the conditions assumed and a frequency of 1 kmc/s, a value of $(1 - n) = 8(10)^{-4} = 800$ N-units would be expected due to the plasma which varies according to f^{-2}. A gradient of one N-unit per meter would produce a net refraction of 10^{-2} radians for a 10 km path. This does not seem entirely unreasonable for frequencies of 1 kmc/s and below. The decreasing electron density with height as expected above the lunar surface would produce an upward curvature.

Some information on the contribution to the phase factor by dust particles is given in Section IIIAe. However, uncertainties in particle size, composition, density gradients, etc., make any estimate at this time pure speculation.

c. Scattering

The principle effect of scattering energy out of the main beam is to attenuate the main wave. This effect is included in the attenuation values given for dust particles, free electrons, and molecules. The attenuation values for the latter two have been shown to be quite small in a homogeneous region, but if the medium has a random, turbulent or "bloby" character, the variations of the macroscopic parameters will cause energy to be scattered over wide angles, providing the scale of the variations is less than a wavelength. On the basis of the total values of refractive index indicated in the previous section, a very small amount of energy would be lost from the main beam for anything close to the expected spatial variations (except possibly for dust clouds), but even though the percentage of the energy scattered is quite small, it may be noticeable on a sensitive radar.

On page 17, it is indicated that an electron density of 10^7 per cm^3, though unlikely, remains a possibility. This is in the same order of magnitude as the earth's ionosphere. F-layer backscatter is sometimes recorded on ionograms for frequencies up to a few tens of mc/s. Whether turbulence in the moon's ionosphere is analogous to that which prevails in the earth's ionosphere is uncertain. However, an ionospheric contribution to the refractive index decreases with the inverse square of frequency and the backscattering coefficient involves an additional falloff as the ratio of the wavelength to mean "blob" size decreases. Therefore, it does not seem possible for free electrons to contribute a measurable backscattering above a few hundred mc/s in the lunar atmosphere.

If the scale of the refractive index variation is large over the distance of a wavelength, a major portion of the scattered energy continues in a dominantly forward direction. Thus the general strength of the wave is not greatly affected, but the energy is diffused to the extent that it tends to obliterate fine detail.

The mean-square phase variations of a wave can be approximately expressed as

$$\overline{\Psi^2} = 50\ \overline{\Delta n^2}\ L\ R/\lambda \text{ radians}^2 \qquad 27$$

In this, $\overline{\Delta n^2}$ is the mean square value of the refractive index variations, L is a typical scale length for the refractive index, R is the radar range (in the turbulent region) and λ is the wavelength. It is assumed that $L \ll R$.

Using this approach it is estimated that detail is lost if $\overline{\Psi^2} > 1$, in which case $\overline{\Delta n^2}$ would be $> \lambda^2/50\ LR$. Since for an ionized medium the refractive index deviation varies as λ^2, this effect would be expected to increase with increasing λ. This indicates that very small deviations in n would produce appreciable effects, as is the case of star scintillation. However, to have any real effect, the scatter pattern of the anomalous "blobs" must be greater than the angle over which energy is received (restricted either by the receiving antenna pattern or the source size). (For this reason the larger planets exhibit little scintillation). The scatter-beam width is crudely λ/L radians, L being the "blob" diameter. Thus only "blobs" whose diameters are less than the wavelength divided by the angle over which energy is received, will contribute strongly to this type of distortion (unless the larger "blobs" are very strong).

It is difficult to draw a final conclusion as to the actual effects of refractive index variations in the lunar atmosphere, but a significant effect on radar propagation would appear unlikely.

d. Reflection

On page 31, it is indicated that

$$|\rho| \approx \Delta n/2n \approx \Delta n/2$$

in which Δn is the change in refractive index at a boundary, n is taken to be near unity and ρ is the reflection coefficient for normal incidence.

When gases are involved, boundaries are not usually abrupt, but the above formula is valid only if the change in refractive index occurs in a distance less than a wavelength. Also, interfaces are not generally a plane, but the validity of the above expression in this respect is preserved only when an interface does not deviate by a half-wavelength in the first Fresnel zone.

It does not seem likely that boundaries for which the gradient in electron density, gases, etc., meet the above requirements will occur very often, but there is a possibility that the temperature gradient near the lunar surface might provide some troublesome reflections.

e. Frequency Dispersion

Frequency dispersion results when the velocity of phase propagation (or attenuation) is principally a function of frequency. If a pulse is transmitted (thus containing a wide range of frequencies) through such a medium, its shape will be distorted. This will certainly result in some smearing of range resolution. Selective absorption occurs to some degree in the postulated lunar atmosphere as pointed out previously. Therefore, this type of degradation cannot be ignored.

f. Faraday Rotation and Wave Splitting

A magnetic field in a plasma produces a bi-refringent medium. The effects on a plane wave entering the region can best be described in terms of two initially circularly polarized waves with opposite rotation. These two component waves propagate with slightly different phase velocities and attenuation rates. If the effective refractive index differs only slightly from its free space value, the main effect is a rotation of the plane of polarization as the wave travels through the magneto-ionic region. If the transmission occurs between linearly polarized antennas, this rotation of polarization may result in the wave and the receiving antenna polarizations being at quadrature so that very little energy enters the receiver. This would not particularly affect circularly polarized waves nor the reception from a large number of linear antennas with random polarizations. This last situation is a moderate representation of back-scattering from a rough surface where the angle of incidence is not normal. Faraday rotations resulting from reflections from a smooth surface, however, might be important in certain situations.

On page 21 , it is noted that the gyromagnetic frequency for electrons in the vicinity of the moon would not exceed 0.1 mc/s. Thus it is permissable to assume this frequency is much lower than the frequency of the impressed field. For this condition the rotation of the plane of polarization, Ω , can be expressed by [3]

$$\Omega = \frac{-e^3}{2\,\omega^2 m^2 C_o \epsilon_o} \int_o^R B_{11} N_e \, dr$$

in which e and m = electronic charge and mass, ω is the impressed angular frequency, C_o = the velocity of wave propagation in free space, ϵ_o is the permittivity of free space, B_{11} is the component of the magnetic flux density along the path of propagation and N_e is the electron density.

Taking B_{11} to equal 3000 gamma (see page 19) and $N_e = 10^7$ per cm^3 (see page 17), the above expression reduces to $\Omega = 70R/f^2$ radians for R in km and f in mc/s.

g. Beyond the Horizon Propagation

On the earth, low-frequency waves are diffracted an appreciable amount over mountain ranges and around the curvature of the earth. Diffraction would also be present on the moon, but there are several things that would lead to a reduction of this phenomena as compared with the terrestrial situation. First, the moon's curvature is much greater making diffraction less effective. Second, conductivity of the lunar surface materials may be below that of the earth; this would reduce surface waves around the curved surface. Third, the fall-off with height of the refractive index above the earth tends to give the rays a downward curvature. If the moon has an electron distribution that is more dense near the surface, this would give the rays an upward curvature at low frequencies.

At short-wave ratio frequencies the earth's ionosphere acts as a waveguide, thus energy can be transmitted over great distances. An analogous situation is not expected on the moon.

Atmospheric turbulence scatters the energy of high-frequency waves beyond the earth's horizon. The absence of a dense atmosphere on the moon would preclude this type of propagation.

Ionized trails of meteors also furnish a mode of long range propagation on earth that is not expected to be effective on the moon because the lunar atmosphere is not dense enough to offer much frictional resistance to meteoric flight.

In short, it appears that it would be rather difficult to propagate any appreciable energy beyond the moon's horizon at any frequency.

h. Antenna Effects

It is visualized that an ion sheath around an antenna might critically affect its impedance and propagation characteristics as well as maximum power handling capability, while corona discharge and irradiation by protons and photons could increase the noise figure of the system. It is anticipated that these effects would not be different near the moon than at any other point in interplanetary space, but future investigations should be conducted to provide answers to these questions.

4. Summary

In summary it can be stated that the absence of firm data plagues any theoretical analyses concerned with the effects of the lunar atmospheric environment on radar propagation. The work performed in this study, however, has considerably narrowed the number of atmospheric factors which might have to be duplicated to completely simulate radar propagation through the lunar atmosphere. These factors are as follows:

vacuum conditions

temperatures

gases

aerosols

electron layer

magnetic field

high energy particle bombardment of the antennas.

These analyses have also demonstrated that the radar frequencies least affected by the lunar atmosphere are probably centered around the lower portion of X-band. This argument is illustrated in Figure IIIA-4 and is further supplemented by the estimated effects (see Figure IIIA-8) of low frequency Faraday rotation and absorption, plus high frequency degradations of frequency dispersion, refractive index diffusion and bending and reflection effects of dust.

This is not to imply that other frequency bands cannot be used, since the degrading effects of the lunar atmosphere are rather mild in all cases where estimates were made.

B. SURFACE AND SHALLOW-SUBSURFACE EFFECTS

A rigorous mathematical treatment of the effects of surface and shallow-subsurface environmental factors is not within the scope of this report, but some general statements concerning these effects should be made.

Reradiation of lunar materials is affected by many surface variables, e.g., compaction, metallic content, moisture content and roughness. Each of these has some control over the reradiated energy picked up by the radar receiver. Therefore, information concerning these variables is theoretically available in the radar output. Whether or not this information actually can be extracted is subject to a number of variables, such as the dynamic range of the receiver and the observers familiarity with the reradiation characteristics of the pertinent materials.

Subsurface materials lead to even more complications. If, for example, a good electrical conductor overlays a poor conductor, reradiation

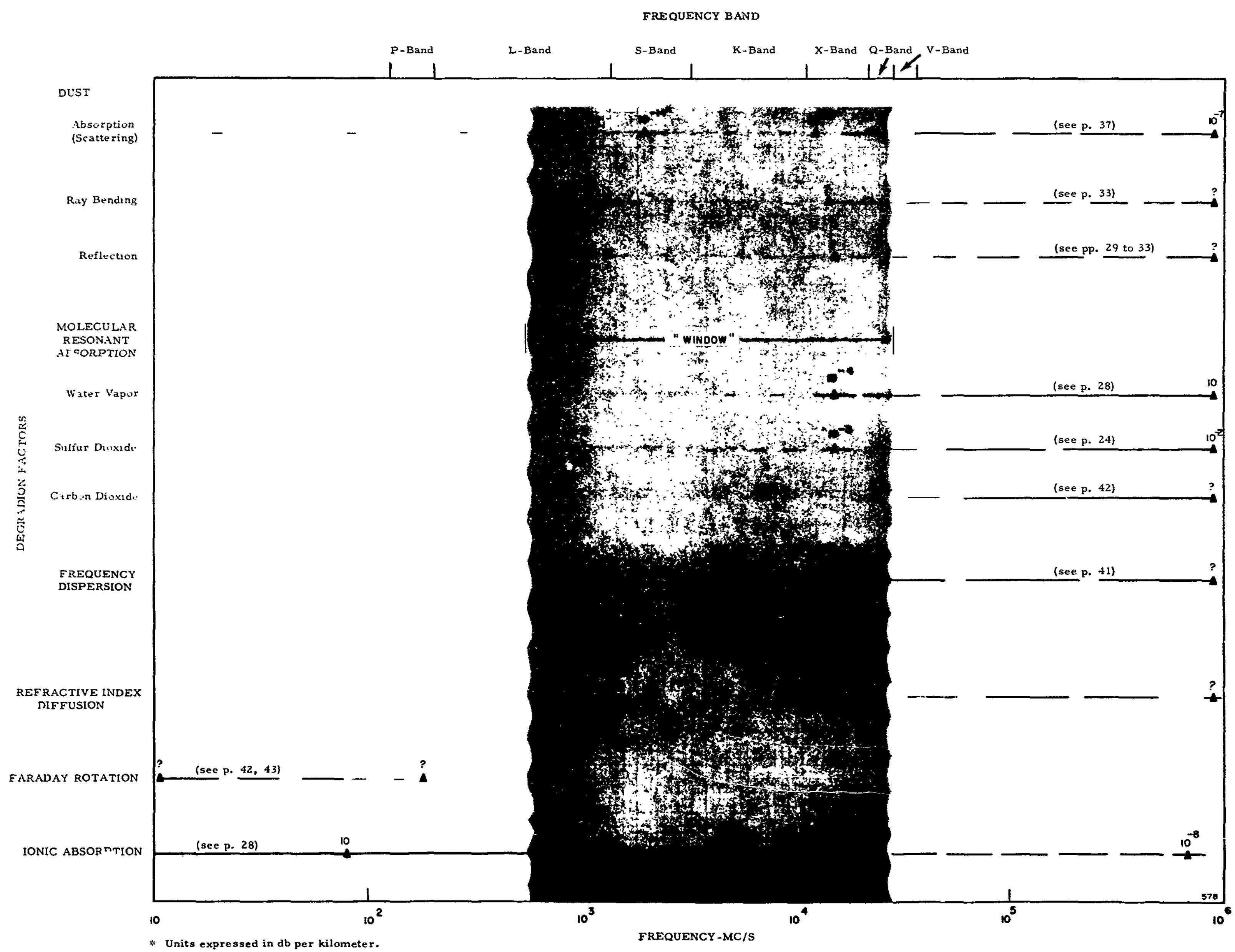


Figure IIIA-8. Lunar Atmosphere Radar "Window" from the good conductor will normally dominate. An exception to this occurs when the attenuation rate of the surface material reduces the signal from the subsurface conductor to less than the low level of the first surface reradiation. Whether or not this will occur depends primarily upon the level of incident radiation, attenuation rate, wavelength, and the degree of conductivity contrasts. An additional effect of a good conductor is to limit the depth of penetration. All such conductors characteristically produce a "skin effect" whereby current flow is set up on the outer surfaces of the conductor and relatively little penetration can be expected. Thus, if there is a good conductor at the surface or in the shallow-subsurface of the lunar terrain, depth to which electromagnetic terrain analysis can be carried out will be restricted.

Knowledge of the physical properties and distribution of lunar materials, therefore, is very important. Unfortunately, actual lunar materials and distributions are not available for such determinations. The next best approach to determine the expected reradiation characteristics of lunar materials is to use combinations and/or modifications of available terrestrial materials (described in Table III) or artificially prepared materials postulated by various authors to have a lunar counterpart.

The exact effects of various terrestrial materials on electromagnetic radiation has received only limited attention; i.e., some theoretical studies have been conducted, terrain materials have been packed in waveguides to measure dielectric constants, and field studies have been conducted which consider only superficial terrain parameters. Such studies have provided useful data which can be accepted as a guide for future work, but they cannot be accepted as applying directly to an operational terrain-analyzing radar output. Table IV is indicative of the type of information available from previous studies, but even these data were collected under circumstances where experimental control was not always the best. In fact, this area of scientific endeavor is comparatively so new that some controlling factors are just now becoming evident.

Fortunately, programs currently are being pursued which undoubtedly will provide data of superior value. For example, a program is being conducted at the U. S. Army Engineer Waterways Experiment Station in Vicksburg, Mississippi, where a radar laboratory (see Appendix B for facility description) has been constructed in which radars operating in four different bands are being used to analyze various soils under controlled conditions. Data from such programs should prove to be extremely useful for future radar analysis work.

As this lunar program continues, some theoretical analyses should be conducted on the surface-subsurface effects on radar propagation. The latest data available from such projects as noted above, should

TABLE IV

ATTENUATION OF ELECTROMAGNETIC ENERGY THROUGH VARIOUS SOIL MEDIUMS [29]

Soil Type	Frequency	ϵ_1/ϵ_o *	Tan δ **	Loss db/m
Sea Water, 17°C				
	10 mc			95
	300 mc			520
	3 kmc			608
	10 kmc			3920
Fresh Water	300 mc	85.2	273	5850
	3 kmc	80.2	2750	79000
	10 kmc	41.0	9500	
Sandy Soil, Dry	10 mc	2.55	.016	.023
	300 mc	2.55	.010	.45
	3 kmc	2.55	.0062	2.5
	10 kmc	2.53	.0036	5.1
Sandy Soil, 2.18% moisture content	10 mc	2.50	.025	.034
	300 mc	2.5	.026	1.2
	3 kmc	2.5	.03	13
	10 kmc	2.5	.065	95
Sandy Soil, 3.88% moisture content	10 mc	4.5	.3	.57
	300 mc	4.5	.03	1.8
	3 kmc	4.40	.046	28
	10 kmc	3.6	.12	205

* ϵ_1/ϵ_o = relative dielectric constant

where ϵ_o = dielectric constant in free space.

ϵ_1 = dielectric constant of a soil.

** Tan $\delta = \frac{\epsilon''}{\epsilon'}$ = dissipation factor or loss tangent

where ϵ'' and ϵ' are properties of the complex permittivity function or, loss factor and dielectric constant, respectively.

TABLE IV (Cont'd)

Soil Type	Frequency	ϵ_1/ϵ_o	Tan δ	Loss db/m
Sandy Soil, 16.8% moisture content	10 mc	20	.35	1.42
	300 mc	20	.03	3.6
	3 kmc	20	.13	165
	10 kmc	13	.29	1000
Loamy Soil, dry	10 mc	2.48	.014	.02
	300 mc	2.47	.0065	.28
	3 kmc	2.44	.0011	.5
	10 kmc	2.44	.0014	2
Loamy Soil, 2.2% moisture content	10 mc	4	.45	.172
	300 mc	3.5	.06	2.97
	3 kmc	3.5	.04	21.5
	10 kmc	3.5	.03	53
Loamy Soil, 13.77% moisture content	10 mc	14.5	1.3	3.93
	300 mc	20	.16	19.2
	3 kmc	20	.12	140
	10 kmc	13.8	.18	630
Clay, dry	10 mc	2.44	.04	5.66
	300 mc	2.38	.020	.85
	3 kmc	2.27	.015	6.2
	10 kmc	2.16	.013	18

TABLE IV (Cont'd)

Soil Type	Frequency	ϵ_1/ϵ_o	Tan δ	Loss db/m
Clay, 20.09% moisture content	10 mc	21.6	1.7	5.6
	300 mc	20	.52	62
	3 kmc	11.3	.25	235
Very dry sandy loam	3 kmc	2	.81	290
Very wet sandy loam	3 kmc	24	1.35	1500
Very dry ground	300 mc	4	.0015	.08
Moist ground	300 mc	30	.02	3
Distilled water	10 mc		.34	
Sea water, 20-25° C	3 kmc	69	.56	1650
Sea water, 28° C	3 kmc	65	.47	1000

be used in these mathematical treatments, but probably the most useful data would be obtained by actual measurement of reradiation from postulated "lunar" materials.

SECTION IV

ENGINEERING CONSIDERATIONS

A. INTRODUCTION

A survey of selected radar and simulation facilities (see Appendix B) indicated that no single facility, existing or proposed, would be adequate for complete simulation of radar analysis of the moon. It was assumed, however, that through modification or combination of these facilities a complete simulation configuration could be obtained. This portion of the study was undertaken to identify engineering problems associated with providing such a facility and suggest possible solutions for these problems. Primary consideration was given radar operation, lunar atmosphere simulation and "lunar" material radar reradiation detection. Design and equipment requirements were investigated and an example of a possible facility arrangement is provided.

B. DESIGN REQUIREMENTS

1. Atmosphere

Work described in Section III-A identified seven conditions, which if simulated properly, should duplicate all aspects of the lunar atmosphere which possibly affect radar propagation. These conditions are listed in Table B-1 of Appendix B in their approximate order of importance. Appropriate value ranges of these conditions are also specified. These data represent the atmospheric model or design goal for the radar facility.

2. Surface and Shallow-Subsurface

Facility requirements for the preparation of lunar surface and shallow-subsurface samples should be studied at a later date (see Section VI). The primary terrestrial materials postulated to have lunar counterparts, however, have been identified in Table III.

It was assumed that radar and environmental simulation equipment problems would be the controlling factors in facility design. Therefore, detailed consideration of lunar surface and shallow-subsurface requirements can be safely postponed.

3. Radar

a. General Considerations

1) Far-Field and Sample Size

Far-field operation should be employed when simulating radar returns from the lunar surface. This is true because the simplifying assumptions normally made in analyzing radar returns (e.g., plane waves) are not valid in near-field applications, thus, making the analysis of near-field data extremely complicated. Therefore, far-field operation is assumed to be necessary.

The distance from the radar antenna to the far-field region is given by:

$$R \geqq \frac{2D^2}{\lambda}$$

where D is the diameter of the antenna and λ is wavelength. Obviously then, distance to the far-field region can be controlled by selection of antenna dimensions. However, antenna dimensions also control beamwidths (or gain). Therefore, as the distance to the far-field region is reduced, beamwidth (hence required sample size) is increased. Reference 29 includes a complete treatment of optimum selection of antenna and sample dimensions for laboratory installations. The results of this work are summarized in Table V.

2) Penetration

It is generally true that penetration of terrain materials is proportional to wavelength.[29] Therefore, multiple frequency capability is desirable for terrain analysis.

3) Summary of Basic Radar Considerations

The size of a facility capable of analyzing samples at radar frequencies are controlled by far-field, beamwidth and penetration requirements. Typical far-field and beamwidth dimensions are given in the following table.

TABLE V

TYPICAL FAR-FIELD AND BEAMWIDTH DIMENSIONS

Band	Frequency kmc	Wave-length (cm)	Antenna Diameter (ft)	Beam-Width (deg)	Far-Field (ft)	Sample Diameter at 90° Incidence (ft)
P	0.3	100.0	8.0	26.7	38.6	21.4
C	6.0	5.0	2.0	6.9	47.5	5.14
X	10.0	3.0	1.5	4.6	41.8	3.63
K_a	35.0	0.86	0.75	2.6	39.5	1.95

b. Frequency Selection

Results of the theoretical analysis in Section IIIA indicate that the portion of the radar spectrum expected to be least affected by the lunar atmosphere is centered around lower X-band. These results plus size requirements imposed by a lunar orbiting vehicle and laboratory samples seem to identify preferred frequencies ranging approximately from C- to K-band (3.9 to 36 kmc).

4. Scaling

The flexibility that scaling affords has aided the experimenter immeasurably in many data collection programs where time and cost for full-scale measurements were prohibitive. Radar cross-section measurements and other related programs are good examples of areas where scaling has been extremely beneficial. Therefore, scaling demands consideration in the present study.

a. Small-Scale Facility

A small-scale facility for simulating radar analysis of the moon is defined as a small bell-jar type arrangement containing a horn or other small radiating antenna. Such a facility would have the advantages of small sample size requirements and relatively low construction cost.

In order to maintain reasonable beamwidth and far-field dimensions, the operating frequencies of such a facility would have to be scaled upward into bands of very little use in actual lunar analysis. Therefore, the reradiation characteristics of the various "lunar" samples used on this facility would have to be extrapolated downward into more useful frequency bands. Unfortunately, terrain analysis by radar has not advanced to the point where extrapolations from one frequency to another can be made with any degree of reliability. Therefore, a small scale facility, would be unsatisfactory for lunar radar analysis studies at this time.

b. Medium-Scale Facility

A medium-scale facility is arbitrarily defined as one in which full-scale, far-field radar is employed, but the antennas are not located within a simulated lunar atmosphere. In this case the "lunar" sample would be placed under a housing, relatively transparent at radar frequencies, where the lunar atmospheric conditions are simulated. Corrections for the effects of the housing on radar transmissions would be required but, since these effects are constant, compensation can be made through calibration procedures.

The advantages of a medium-scale facility include full-scale radar operation and fairly small volumetric requirements for a simulated lunar atmosphere. The disadvantage of such an arrangement is that the propagation path is not entirely within the simulated lunar atmosphere.

c. Large-Scale Facility

A large-scale facility is defined as one in which the radar antennas, the propagation path and the "lunar" sample are all within a simulated lunar atmosphere. An example of this type of facility is shown in Figure B-3, Appendix B.

An obvious advantage of such a facility is complete environmental control. Disadvantages are:

1) Compatibility; electromagnetic propagation in such an enclosure will lead to undesirable reflections unless absorbent materials are used extensively. Use of such materials on the chamber walls would prohibit required cold-wall operations.

2) Cost; the dimensional requirements discussed previously in this section (See Table V) specify a propagation path of at least 38 feet. Thus, even a large facility such as the one shown in Figure B-3 of Appendix B would be unsuitable unless the arch is about 50 feet high. The U. S. Army Engineer Research and Development Laboratories have estimated the cost of a 32.8 foot facility of this type to be about 6,000,000 dollars.[96]

5. Conclusions

Small-scale facilities are currently unsatisfactory for simulating radar analysis of the moon primarily because of frequency scaling difficulties. Large-scale facilities appear to be excluded because of their high cost. (No facilities of this type currently exist, and construction cost would be more than 6,000,000 dollars.) Medium-scale facilities appear to be the best selection for the following reasons: a) laboratories of this type are already in existence and amenable to required modifications; b) full-scale radar operation is possible; c) the effects of the earth's atmosphere on radar propagation over the relatively short path lengths involved are not expected to be significant unless anomalous concentrations of contaminents occur. Therefore, only medium-scale facilities are considered in the remaining portions of this report.

C. EQUIPMENT REQUIREMENTS

1. Vacuum

a. Simulation Requirements

Estimates of the pressures to be encountered at the lunar surface range from 10^{-7} to 10^{-16} Torr (see Table B-1 of Appendix B). The lowest operational pressure presently obtainable in a medium-sized simulation facility is 10^{-9} Torr (see Table B-2 of Appendix B). For a medium-scale radar facility (with a simulator volume of approximately 200 cubic feet), a pressure of approximately 10^{-7} Torr is required.

b. Typical Equipments for a Medium-Scale Facility

Selection of proper vacuum equipments for a lunar environment simulation chamber is dependent upon the following factors:

- size of chamber
- pump-down time requirements
- vacuum requirements (degree of vacuum)
- outgassing rates for equipment or materials within the chamber
- leakage

Therefore, equipments must be selected with care. For example, if relatively rapid pump-down time is specified and equipment selection is based solely upon this figure and chamber size, it is quite possible that outgassing of introduced "lunar" samples will be a serious problem.

Most high vacuum equipments logically fall into two groups, i.e., those which vent directly into the atmosphere and those which require buffer pump or forepumps. Table VI includes examples of both types.

From the above considerations, it appears that an oil-sealed rotary type forepump and two 20-inch oil diffusion pumps would be adequate for a lunar radar facility. Douglas Aircraft Company, Inc., for example, has a 125-cubic foot, high altitude chamber which uses a single 32-inch oil diffusion pump as their main vacuum source[71] to obtain pressures equivalent to 10^{-7} Torr. Johns Hopkins University uses a pair of 20-inch oil diffusion pumps to obtain a pressure of 10^{-6} Torr in a chamber of approximately 220-cubic feet.[71]

Defining pump size in relation to chamber size, however, is only an approximation of actual requirements. The final pump configuration

TABLE VI

HIGH VACUUM EQUIPMENT[96]

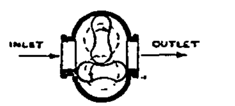
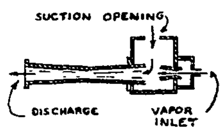
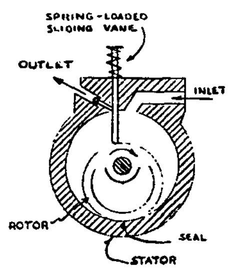
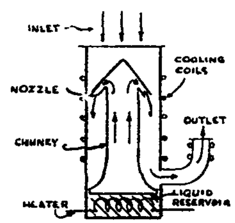
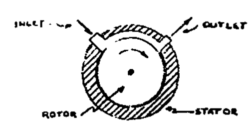
Type	Pressure Range (mm Hg abs.) Ultimate Pressure	Pressure Range (mm Hg abs.) Limiting Forepressure		Operating Principle	Advantages	Disadvantages
(1) Roots Type Blower	150	760 (1 atm)		Counter-rotating meshing lobes alternately trap gas on inlet side and discharge to high pressure side.	High capacity; no contamination (runs dry); relatively simple; pumps all gases.	Backstreaming from discharge to inlet lowers efficiency; close tolerances; high speed.
(2) Ejectors 1 Stage 2 Stage 3 Stage 5 Stage	50-100 25-50 0.1 0.03	760 760 760 760		High velocity vapor jet (steam, oil, or mercury) discharges across suction opening; gas entrained by vapor stream, carried into venturi and ejected at higher pressure.	No moving parts; no controls; pumps all gases; no special power supply; small size; inexpensive.	Can contaminate system; capacity control difficult.
(3) Oil-Sealed Rotary Pump (1 Stage)	0.05	760		Gas compressed to very small volume by rotating eccentric; sliding vane separates inlet from outlet; small space between Rotor and Stator sealed with oil.	Simple; reliable; high capacity; can be controlled; wide variety available; pumps all gases.	Can contaminate system.
(4) Oil-Sealed Rotary + Cold Trap (1 or 2 Stage)	0.01	760		Cold trap inserted between pump inlet and vacuum enclosure to condense oil vapor which might backstream. See (12).	Same as above (3).	Same as above (3).
(5) Multi-Stage Oil-Sealed Rotary Pump + Cold Trap	0.005	760		Same as above, except several pumps used in series.	Same as above (3).	Same as above (3).
(6) Oil Diffusion Pump + Cold Trap	10^{-10}	2×10^{-1}		Low vapor pressure liquid (oil or mercury) boiled; vapor rises in chimney and ejected downward at high velocity from nozzle; gas molecules enter vapor stream, collide with vapor molecules, and are given downward velocity component: backing pump removes from outlet; vapor condensed on cold wall and returned to boiler.	No moving parts; no controls; pumps all gases; no special power supply; small size; inexpensive.	Contaminates system and therefore requires liquid nitrogen cold trap; requires forepump.
(7) Mercury Diffusion Pump + Cold Trap	10^{-12}	3×10^{-1}			Same as above (6).	Contaminates system and therefore requires liquid nitrogen cold trap; requires forepump; mercury potentially hazardous to personnel.

TABLE VI (Cont'd)

HIGH VACUUM EQUIPMENT

Type	Pressure Range (mm Hg abs.) Ultimate Pressure	Limiting Forepressure	Operating Principle	Advantages	Disadvantages
(8) Electro-Magnetic Pump	10^{-6} to 10^{-12}	$3\text{-}5 \times 10^{-4}$	Gas molecules ionized by source such as thermal emission cathode; gas ions then propelled by use of electromagnetic force.	No contaminations; pumps all gases.	Special power supply; large size; requires forepump; high power; expensive.
(9) Ion-Gettering Pump: (a) Hot Cathode (b) Cold Cathode	10^{-7}-10^{-9} 10^{-9}-10^{-12}	10^{-3} 2×10^{-2}	Gas molecules ionized and accelerated as above (8); ions then caused to impinge on fresh active metallic lattice, where they react or are trapped on or within lattice. Two types in use.	Little or no contamination; pumps in sealed system; requires forepump only for start-up; low power.	Complex getter-feeding device, controls, and power supply; hardly pumps noble gases or methane; subject to contamination.
(10) Molecular Drag Pump	10^{-7}	1.0	 High-speed rotor drags molecules from inlet to outlet.	Pumps all gases; no contamination except seal lubricants.	High-speed moving parts; expensive; requires forepump or additional stages.
(11) Gettering (Barium)	10^{-7}		Getter is a substance which takes up gas at low pressure by adsorption, solution, or chemical combination. Barium, titanium, misch metal and zirconium typical adsorbent-type getters.	Good for auxiliary clean-up.	Consumes expensive material and leaves residue.
(12) Cold Trap	Depends on temperature		Liquefies or freezes out condensables by low temperature refrigeration. Dry ice, liquid air, liquid nitrogen commonly used.	Simple; no moving parts.	Requires refrigerant.

can only be determined when the conductance of associated vacuum piping, the amount of outgassing to be expected from the "lunar" samples and from any auxiliary equipment within the chamber, leakage, and the nature of the gas to be pumped are known.

2. Maximum Temperature

a. Simulation Requirements

Maximum temperatures at the lunar surface have been determined to be approximately 407°K (see Table B-1 of Appendix B). This figure is based upon experimental measurements and it is assumed (in this report) that the heating is due entirely to energy received from the sun. The solar constant* has been accepted as the solar energy level for the lunar surface. This value is given as 1.94 calories per square centimeter per minute (1352 watts per square meter) the wavelength range of solar radiation considered in this section ranges from approximately 0.3 to 2.0 microns.

Two conditions must be duplicated if solar radiation is to be simulated. These conditions are intensity (the solar constant) and energy distribution. Since the basic requirement is high temperature, simulation equipments must reproduce infrared radiation intensities and energy distribution most faithfully. This assumption is made even though little is known about the nature of lunar surface materials and whether or not the shorter wavelength radiation contributes to the surface temperature through particle excitation.

b. Typical Equipments for Medium-Scale Facility

Applicable equipments for simulating solar radiation are listed in Table VII. Of these equipments the most adaptable are xenon short-arc or standard 3000°K incandescent lamps used in conjunction with ultraviolet lamps.[96] A medium-size facility would require a single 10 kw xenon lamp, or a number of smaller lamps totaling 10 kw, to illuminate a sample area of approximately 20 square feet. Three, 1 kw incandescent lamps employed in conjunction with mercury vapor lamps would provide the same spectral illumination of the area.

An advantage in using xenon lamps, rather than incandescent lamps, is that xenon lamp intensity can be varied over an extreme range without causing spectral shift. For radar analysis research, lamps cannot be arranged to provide vertical incidence illumination of the sample because of radar equipment configuration. The range of available intensities using xenon lamps should permit mounting in other than normal positions and still duplicate the solar constant energy level.

* The solar constant is defined as the energy received from the sun at normal incidence just outside the earth's atmosphere.

TABLE VII

SOLAR SIMULATION METHODOLOGY[16]

Method	Type	Advantages	Disadvantages
6000^oK Blackbody (unavailable, ideal)			
Carbon Arc	a) Crater anode as light source and object of optical system b) Hot vapors as radiation source, e.g., strong blown arc.	- excellent solar spectrum match - available - cylindrical source (b)	- high maintenance costs - short duration - cumbersome anode and cathode drive mechanisms - electrical to radiant efficiency 1 to 2% - vaporizing electrode materials results in deposition of solids on optical components of projection systems.
Pressurized Mercury Arc Lamps*	a) Low pressure lamps emitting spectra characteristic of Mercury b) High pressure lamps possessing increased background continuum	- good solar match in the narrow range near ultraviolet to visible - adaptable to multiple source application.	- even at high pressures the discharge fails to achieve blackbody conditions - does not approximate solar spectra in 1800 to 30,000 A region.
Xenon/Xenon-Mercury Short Arc Lamps**	a) Xenon lamps b) Xenon-Mercury Lamps	- Long life (up to 1000 hours) - Good solar spectrum response up to 4000A, but considerable deviation occurs in the visual. - Stable discharge. - Ease of operation. - Relatively high collection efficiencies.	- Poor spectral response in infrared region - Radiant energy diminished up to 25% during life due to tungsten depositing on quartz envelope.

TABLE VII (Cont'd)

Method	Type	Advantages	Disadvantages
Tungsten Lamps		- Good solar match in 4200 to 10,000 A region***	- Poor solar match in ultraviolet and infrared regions. - Operating temperature (3,000°K) and thermal emissivity gives continuum with peak displaced from solar peak. - Poor efficiency
Arc Plasma Generators		- Unlimited power possible with single unit. - Good optical efficiency attained by using small cylindrical plasma. - Spectral distribution easily altered by changing input power or by gas control. - Ease of operation and maintenance. - Good conversion efficiencies**** - Good stability	- Short life (48 hrs) due to anode erosion.

* Spectrum emitted depends on internal pressure used which ranges from 2 to 110 atmospheres.

** Tungsten electrodes sealed in quartz envelopes with gas enclosed. Available up to 2.5 kw input with 48% electrical to radiant efficiency. Approximately 20 kw input required for 1 kw at target.

*** Achieved by combining lamps and filters.

**** Increased to 85% using transpiration.

3. Minimum Temperature

a. Simulation Requirements

The lowest temperature expected at the lunar surface is estimated to be approximately $90^{o}K$.

b. Typical Equipment for Medium-Scale Facility

For a medium-scale facility the most suitable coolant mechanism appears to be a liquid nitrogen refrigeration system (liquid nitrogen boiling point = $77.3^{o}K$).

Two types of liquid nitrogen systems are available, i.e.,(1) single pass systems, in which liquid nitrogen is exhausted after one pass, and (2) closed re-cycling systems.

The closed re-cycling system is preferred for a medium-scale facility because exhausting concentrated nitrogen vapor in the vicinity of radar equipments may create operational problems. Nitrogen vapor itself is not expected to degrade radar transmission, but the low temperature exhaust could produce water vapor condensation clouds which would affect radar propagation.

Of the many closed-system refrigeration methods utilizing liquid nitrogen, three appear best suited for medium-size facilities. These are:[96]

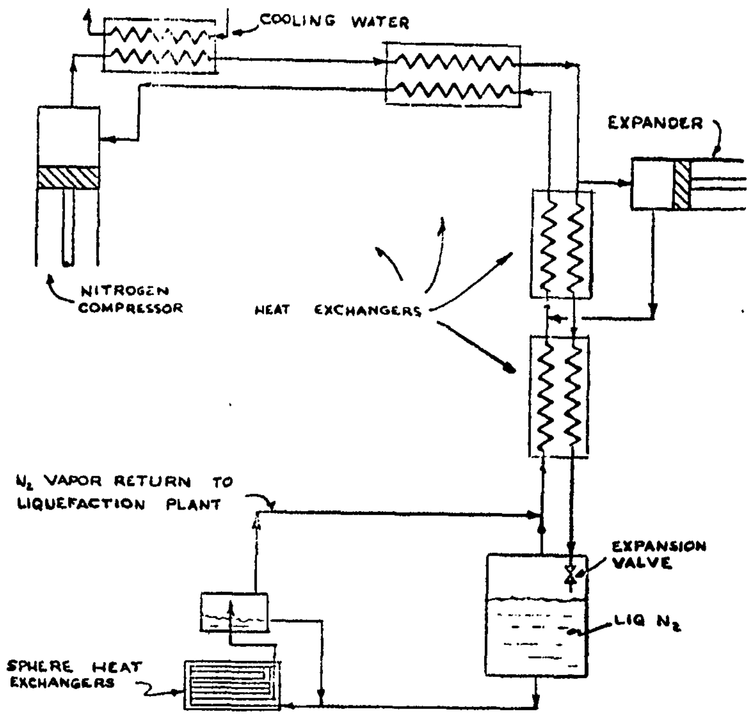
Linde High-Pressure Process

Claude System

Cascade System

In the Linde high-pressure process, refrigeration is accomplished in two stages by Joule - Thompson expansion. In the Claude system refrigeration is produced by expansion in an engine with final refrigeration usually produced by a Joule - Thompson expansion. The Cascade system lowers temperatures by a three-fluid external process. This is in contrast to the previous types where almost all refrigeration originates in the process gas. Typical fluids for a three-fluid system are ammonia, ethylene and methane.

For the medium-size simulator discussed herein, either the Linde high pressure or the Claude system appears applicable. Figure IV C-1 is a block diagram of a Claude cycle.



The cost of operating a closed recycling refrigerant system is usually much less than an open system because of reduced recharging requirements. Initial equipment costs for the closed system, however, will be much greater because a liquefaction cycle is required.

Figure IVC-1\. Claude Cycle

4. Gases

a. Simulation Requirements

The critical constituents of the lunar atmosphere as given in Table B-1 of Appendix B are:

Water Vapor
Sulfur Dioxide
Carbon Dioxide

The density of these gases in the lunar atmosphere has not been accurately determined. Dollfus[20] estimates the lunar atmospheric density to be less than 10^{10} molecules per cubic centimeter. Since it is highly unlikely that the atmosphere would be made up of only one of the above-mentioned constituents, a simulation density maximum for each can be considered to be 10^{10} molecules per cm.

b. Typical Equipments for a Medium-Scale Facility

The design of a complete facility for radar analysis of the moon should include a means for varying atmospheric constituents and density.

This can be accomplished most readily by injecting concentrated amounts of each gas or a selected group of gases into the evacuated chamber, and repeating the pump-down to the desired vacuum.

Equipments necessary to accomplish the injection and to monitor the gas concentrations appear to be well within the state-of-the-art and should not be a major engineering problem. Premixed gases can be obtained in desired concentrations for injection into the simulation chamber.

5. Aerosols

a. Simulation Requirements

Aerosols in the lunar atmosphere appear to come from two sources; dust particles kicked up by meteoritic impact or other crustal disturbances, and cosmic dust falling to the lunar surface. Since the aerosol concentration in the lunar atmosphere has not been determined quantitatively, simulation requirements cannot be established. Therefore, simulation equipments would have to be capable of varying the concentrations, composition, and dimensions of aerosol particles over a fairly wide range.

b. Typical Equipments for a Medium-Scale Facility

Equipments for injecting aerosols into the environment chamber could be quite varied due to the range of requirements. It appears, however, that suitable injection equipments could be engineered with relative ease and low expense.

6. Radiation (High-Energy Particle Bombardment)

a. Simulation Requirements

Ionizing radiations incident upon the lunar surface are expected to affect lunar soils in a variety of ways. Such effects could include darkening of lunar soils, welding of soil particles, and the creation of a chemically unstable and highly reactive surface. One of the most important forms of radiation consists of ionized, hydrogen plasma with proton energies of several kilovolts.[46] The proton flux density incident upon the lunar surface approximates 10^8 to 10^{12} protons per cm^2-sec (see Table I). The radiation energy levels expected at the lunar surface varies from a few ev to hard cosmic rays of 1000 Bev or more. Therefore, an upper limit of 1000 Bev is tentatively set as a simulation requirement.

b. Typical Equipments for a Medium-Scale Facility

A wide range of particle energies can be simulated by using available ion sources and electrostatic acceleration systems. For example, in the MIT cyclotron, it is possible to accelerate deuterons to velocities equivalent to that attained by accelerating the same particles through a potential difference of 18 million volts (or 18 mev). Use of a frequency modulated cyclotron increases this to several hundred million volts. Similarly, electron acceleration can be accomplished by using a betatron or Van deGraaff type generator.[74] Higher energy particles can be achieved by the use of various radioactive materials.

Very little is known concerning the effects of high-energy particle bombardment on the possible lunar surface materials.[46] Therefore, stipulation of precise equipments to generate these particles (considering the variety of particle types and relative energy levels) can only be done arbitrarily. At the present time it appears that the irradiation would not have to occur within the lunar atmospheric simulation chamber and samples could be irradiated in some other facility. An irradiated sample of the size stipulated in Table V, would require particle generators and accelerators of fairly high capacities if the irradiations are to be completed in a reasonable length of time. Therefore, sample irradiation equipment is not considered to be part of the lunar simulation facility.

7. Ionization

a. Simulation Requirement

Electron densities in the lunar atmosphere are estimated to range from $10^3/m^3$ to $10^7/cm^3$.[92] The heaviest concentration of these electrons is expected to exist just above the lunar surface.[79] If the latter were not true, i.e., if the lunar ionosphere occurred at an altitude of several hundreds of meters, simulating this condition in proper perspective relative to the lunar surface would be difficult if not impossible. However, if the lunar ionosphere is assumed to exist near the lunar surface, simulation of this condition is relatively simple.

b. Typical Equipments for a Medium-Scale Facility

Establishing the required electron densities can be accomplished by using off-the-shelf equipments. For example, x-ray bombardment or electron boil-off processes, such as a heated cesium cylinder can be employed. From the standpoint of cost and power requirements the latter method appears to be most suitable.

8. Magnetic Field

a. Simulation Requirements

The magnetic field strength of the moon has been estimated to range from 2.5 gamma[73] to as high as 3000 gamma.[35] These values are, of course, much lower than the earth's magnetic field (25,000 to 100,000 gamma). Simulating the lunar field within a restricted area on the earth's surface, therefore, requires that the earth's natural field be drastically reduced.

b. Typical Equipments for a Medium-Scale Facility

There are two methods commonly used to reduce the effects of the earth's magnetic field: magnetic shielding and Helmholtz coils. Shielding is generally used where the elimination of induced diurnal gradients is not critical. Helmholtz coils and associated current regulators are usually employed when a steady field is required.

Simulating the magnetic field of the moon in the facility under consideration by the use of magnetic shielding is impractical because the required shielding material would not be transparent at radar frequencies. Helmholtz coils appear to be the best approach both from transparency considerations and inherent flexibility.

A medium-size facility enclosing something less than 200 cubic feet would require a coil 15 to 20 feet in diameter with about 20 turns carrying three to four ampheres (the coil in this case is external to the chamber). Such a coil, if properly oriented to partially nullify the earth's field, could produce the postulated lunar magnetic intensities.

D. EXAMPLE OF A MEDIUM-SCALE FACILITY ARRANGEMENT

1. Introduction

As defined in Section IVB3, a medium-scale simulation facility is one in which radar may be used in full-scale but the antennas are not located within a simulated lunar atmosphere. A facility which meets this definition and is amenable to modification for lunar radar analysis has been designed by Texas Instruments and built at U. S. Army Engineer Waterways Experiment Station in Vicksburg, Mississippi. Construction of a lunar atmospheric simulation test chamber large enough to contain a 30 cubic foot "lunar" surface-material sample (surface area $\approx$ 20 sq ft.) would provide a simulation configuration suitable for detailed radar analysis of possible lunar materials.

2. Radar Configuration

The Waterways Experiment Station Terrain Analysis Radar (WESTAR) laboratory provides for far-field radar operation in the K_a-, X-, C-, and P-bands. The laboratory housing is in the form of a 50-foot radius arch open at both ends. Radar antennas are mounted on a carriage designed to traverse one-half of the arch. Terrain sample materials, positioned on the ground beneath the apex of the arch, can be illuminated with radar energy at incident angles ranging from 30 to 90 degrees.

Figure IV D-1 is a block diagram showing the component arrangement for one radar band. The other three radars possess similar component arrangement. A photograph of this facility is included as Figure B-2 in Appendix B.

3. Modification Requirements

a. Radar Modifications

The existing WESTAR radar and recording equipment is adequate for radar analysis of "lunar" samples.

b. Facility Modifications

Modification of the type illustrated in Figures IVD-2 and 3 would equip the WESTAR facility for complete simulation of radar analysis of "lunar" materials.

4. Complete Facility Configuration

Figure IVD-4 shows the complete simulation facility configuration.

5. Cost Estimate

A detailed cost analysis of a complete medium-scale facility was not within the scope of this study. However, the cost of engineering and modifying an existing radar facility (such as WESTAR) to meet all simulation requirements has been estimated at 500,000 dollars. Fabrication of a lunar-environment sample chamber represents the principal expense.

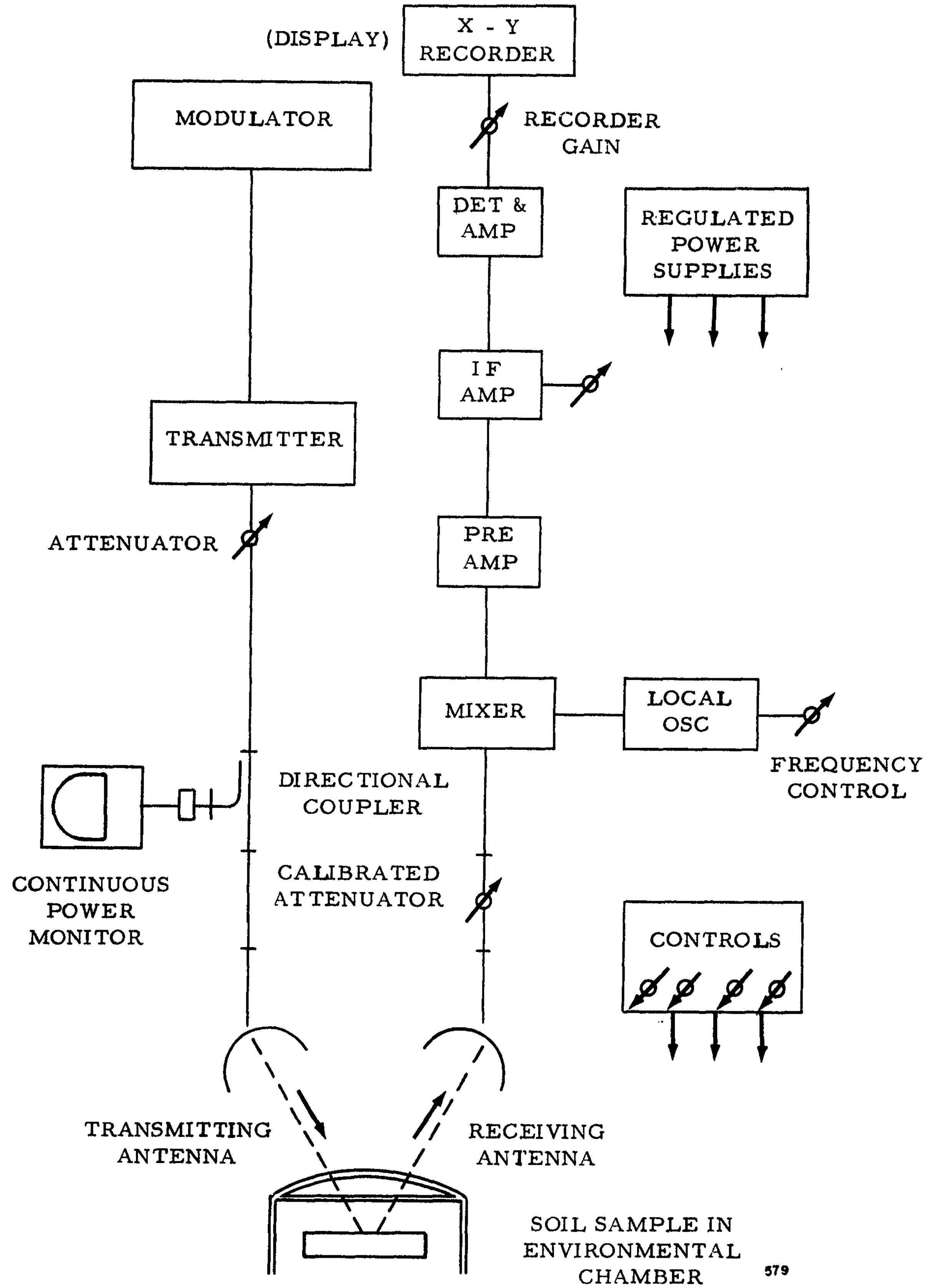
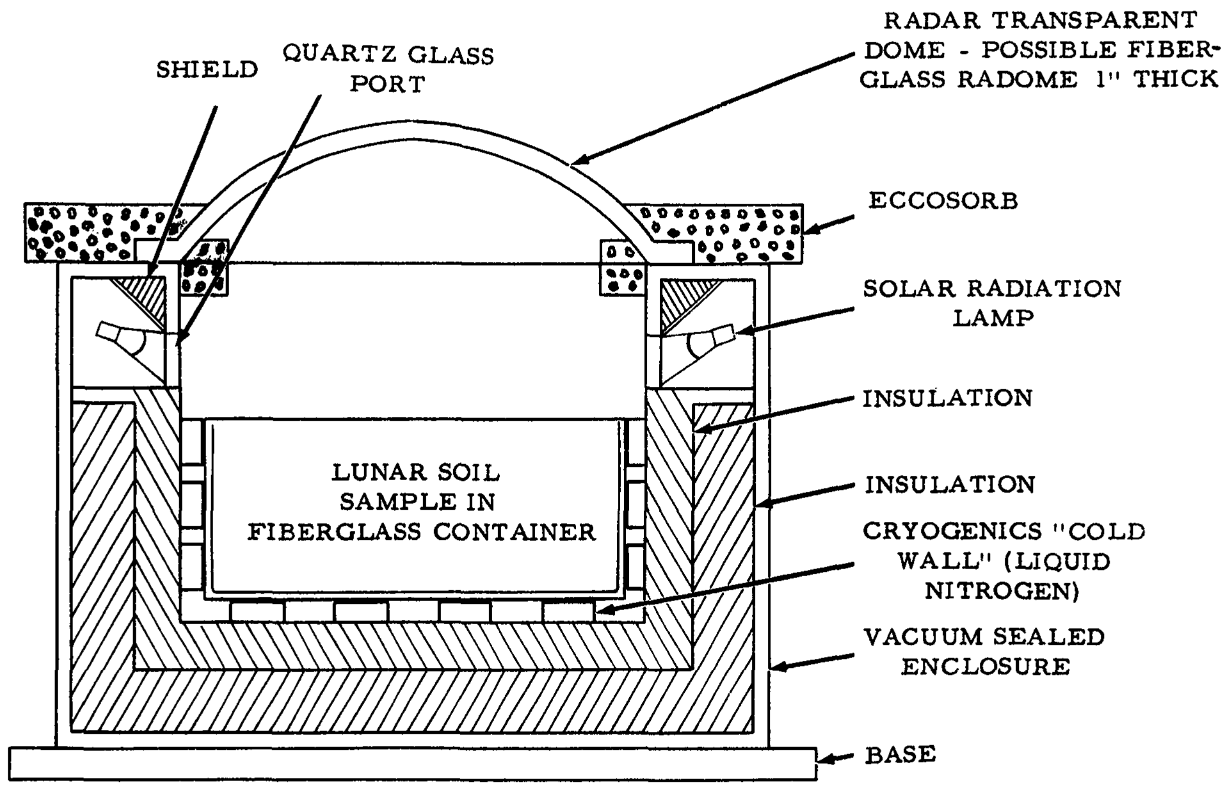


Figure IVD-1. Radar Equipment Block Diagram

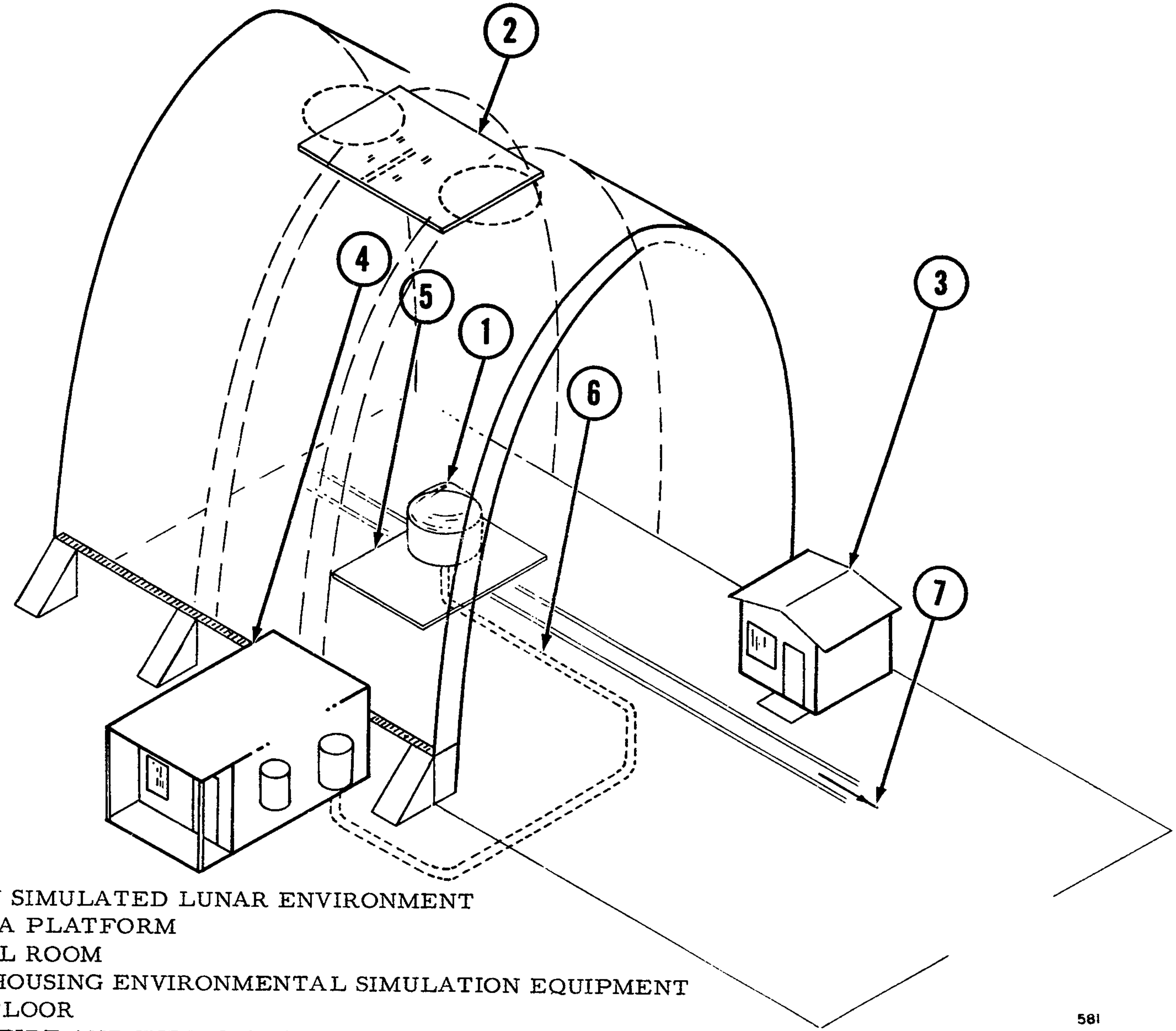


Dimensions:

'Lunar' Soil Sample -
5 ft. in diameter x 1.5 ft. deep

Simulation Chamber
Interior Volume 120 cu. ft.

Figure IVD-2. Cross Section of Soil Sample Cart



1. SOIL SAMPLE IN SIMULATED LUNAR ENVIRONMENT
2. RADAR ANTENNA PLATFORM
3. RADAR CONTROL ROOM
4. BUILDING FOR HOUSING ENVIRONMENTAL SIMULATION EQUIPMENT
5. ECCOSORB ON FLOOR
6. UNDERGROUND PIPE AND WIRING CHANNEL FOR ENVIRONMENTAL CHAMBER
7. TO SAMPLE PREPARATION FACILITY

Figure IVD-3. Vicksburg Radar Laboratory Modified for Lunar Radar Simulation

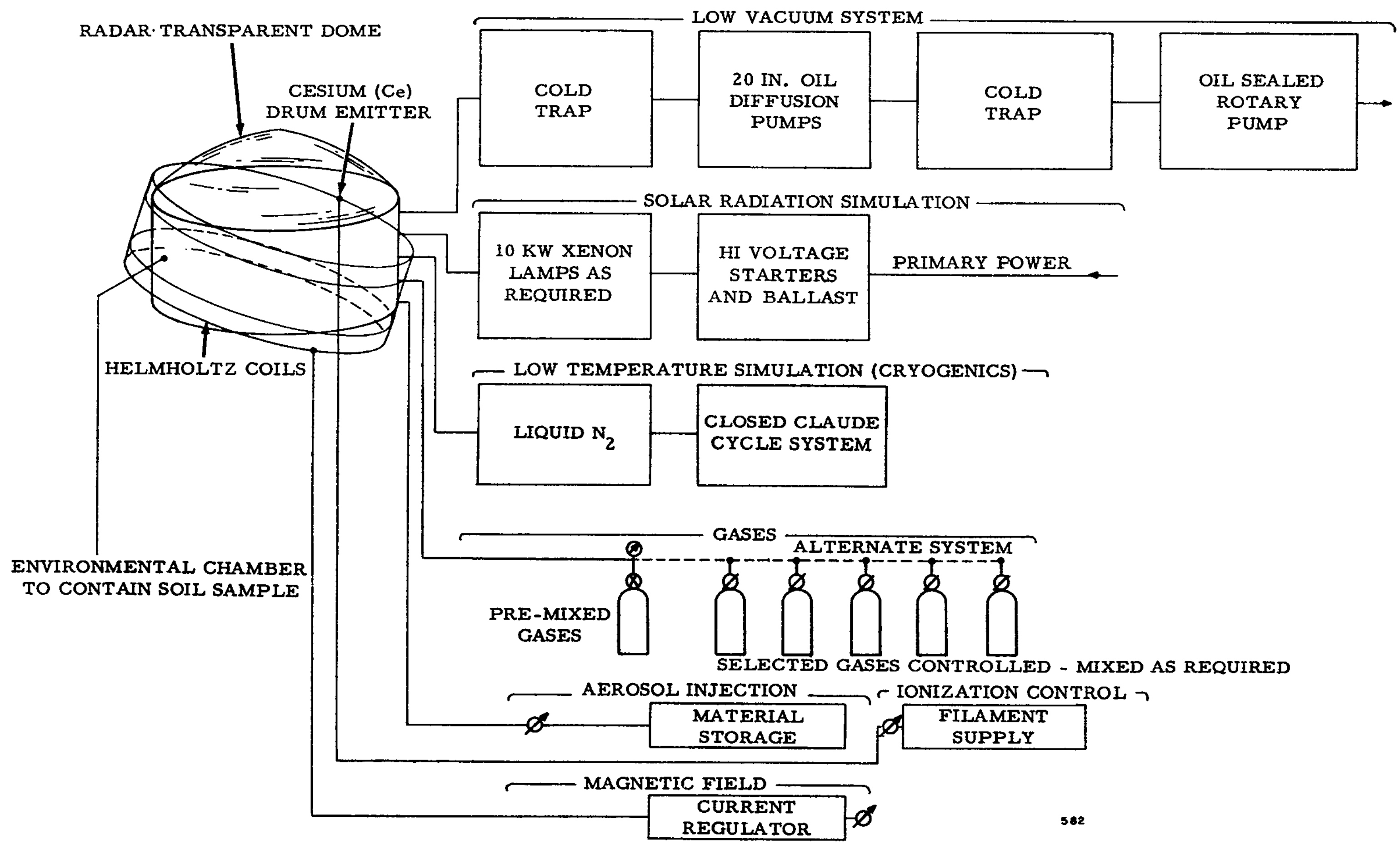


Figure IVD-4. Block Diagram of Lunar Environmental Simulation System

SECTION V

SUMMARY AND CONCLUSIONS

A. RADAR RERADIATION MEASUREMENT REQUIREMENTS

The limitations of radar as a remote terrain analyzing tool are unknown. Both theory[17, 28] and practice [40, 41, 97] have demonstrated the potentialities of radar for such work, but the foundations for broad application are still being laid. Laboratory measurement of radar frequency reradiation from terrestrial soil samples under controlled conditions has just begun. Nonetheless, available data indicate that radar can be a potent tool for terrain analysis.

The possible use of radar in non-contact analysis of portions of the earth's surface is of great significance, and its potentialities in lunar and space application are even more impressive. At the present time, however, surface information is still required for interpretation of radar data. Some terrestrial interpretation work can be carried out by geologists or others familiar with the earth's materials [41] but in order to evolve from this art to a more universally applicable scientific approach, observed radar returns must be correlated with laboratory results so that the controlling factors can be identified.

If the full potential of radar is to be realized in lunar exploration, signatures of lunar materials must first be identified in the laboratory. At the present time, however, no laboratory reradiation measurements of lunar materials are possible because actual lunar samples are not available. Therefore, artificially prepared materials and/or naturally-occurring terrestrial materials which are postulated to be on the moon, must be utilized. A laboratory reradiation measurement program employing such materials would assure a maximum state-of-readiness for future lunar exploration programs.

B. ATMOSPHERIC

1. Theoretical Analysis Results

Theoretical analyses have identified seven environmental factors which would require simulation for a complete and comprehensive study of radar propagation through the lunar atmosphere. These factors are listed and defined in Appendix B, Table B-1, in their approximate order of importance.

Any analysis is only as good as its input data. In the case of a lunar atmospheric analysis, the quality of the input data could cast serious doubts on the value of any work, particularly if the selection of data were subjective; i.e., any one person's best guess. To avoid this pitfall the analyses contained in this report were carried out using the extreme values (of factors that would affect radar propagation) published by various authors. The results of these analyses have shown that the effects of the lunar atmosphere on radar propagation will, in all probability, be relatively small. This is particularly true in the lower X-band region (see Figure IIIA-8).

2. Engineering Considerations

The engineering study described in Section IV indicated that a medium-scale facility (as defined on page 53) is the most desirable for simulating radar analysis of the moon. Brief consideration of the engineering problems involved in providing a complete simulation facility also revealed that all required equipments are within the state-of-the-art. A more detailed analysis of the engineering design and costs should be made before a facility construction or modification program is initiated. It can be stated, however, that the equipment and engineering costs required to completely modify an existing radar facility of the required type, are estimated to be 500,000 dollars. (The desirability of actually modifying such a facility is discussed below.) Facility requirements for sample preparation were not covered because of time limitations, but should be considered in future work.

3. Simulation Requirements

An engineering study has indicated the type of laboratory equipment and arrangement that would be required if very careful and exact measurements are to be taken of radar reradiation signatures of possible lunar materials. However, the fact that (a) actual lunar materials are not available, and (b) terrestrial lunar equivalents are speculative must be weighed against the time and money required for the development of a complete simulation facility. On the basis of this evaluation it does not appear advisable to make such expenditures if (a) gross reradiation measurements are to be made and (b) an adequate, but less sophisticated, radar facility can be made available. In view of the relatively minor effects of the lunar atmosphere on radar propagation (as determined by theoretical analysis in Section III) and the embryonic status of radar terrain analysis (which does not permit reliable interpretation of detailed measurements), simple radar reradiation measurements of postulated lunar materials in an unmodified WESTAR-type facility would be of great value.

The WESTAR facility, which is mentioned in Section IV and described in Appendix B, would adequately fulfill all immediate requirements. Radars centered around lower X-band are available and the effects of the earth's atmosphere over the facility's fifty foot transmission path are small.

In fact, transmission media effects over this distance may roughly correspond to expected lunar atmospheric effects. Data collection in such a facility would be relatively inexpensive and is recommended prior to detailed consideration of modification of an existing facility or construction of a complete medium-scale facility. It is recognized, however, that a facility for simulating selected lunar atmospheric and surface conditions may be required for verification of radar reradiation measurements and theoretical determinations.

4. Problem Areas

This study has pinpointed some basic problem areas where data were not available. The lack of data in these areas may not be critical at this time, but does require investigation at the earliest opportunity. Problem areas include:

carbon dioxide spectral absorption effects (particularly in the radar spectrum)

solar radiation effects on radar antennas (study possible secondary emission effects, e.g., impedance mismatch)

General up-dating of all theoretical analyses (e.g., Section IIIA) should be undertaken as data become available.

C. SURFACE AND SHALLOW-SUBSURFACE

1. Simulation Requirements

A great deal of experimentation, observation, and pure speculation has been published concerning the nature and distribution of lunar materials. Some "experts" make very strong and seemingly logical arguments which apparently are in direct opposition to other forceful and logical opinions. Until the truth is determined by actual sampling of the lunar surface, the safest way of modeling lunar materials is to consider everyone's opinion to be equally valid. Table III is a compilation of opinions and should be used as a guide for future lunar-surface modeling work.

It should be mentioned that any modeling for radar reradiation work will have to be at full-scale, because the state-of-the-art in radar terrain analysis does not permit extrapolation from one frequency band to another. This is another reason for using a full-scale far-field facility such as WESTAR.

2. Radiation Effects

Only recently have experiments been conducted to determine the effects of solar radiation (particularly proton bombardment) on various materials. Wehner, et al, have determined sputtering yields for silver (as quoted by Green).[43] Hapke's experiments, although qualitative, were performed on a wider range of materials and probably provide the best indications of what to expect of lunar material alteration due to proton irradiation. As a result of his experiments, Hapke makes the statement: "Hence it is to be expected that materials rich in Fe, Cu or other metals of low oxidation potential, such as fayalite ($Fe_2 SiO_4$), will be darkened fairly rapidly by proton bombardment. <u>This darkening is due to the formation of free metal near the surface of the grain.</u>* Such minerals are found more often in basic than in acidic rock. There are a number of reasons for believing that the moon is composed of basic rock. Hence it is highly likely that the lunar surface will be darkened by proton bombardment."[46]

Quite obviously such alterations could change the reradiation signatures of lunar materials at radar frequencies. It will be necessary, therefore, to include in a measurement program irradiated specimens of postulated lunar materials in order to determine signature changes of materials exposed to proton bombardment on the lunar surface.

D. FEASIBILITY OF SIMULATING RADAR ANALYSIS OF THE MOON

Based on currently available data and methods of analysis, this study has shown that it is feasible to simulate radar analysis of the moon using existing radar facilities and postulated terrestrial equivalents of lunar materials.

* Editor's underlining

SECTION VI

RECOMMENDATIONS

It is recommended that:

a. Techniques and methods be developed for preparing replicas of possible lunar surface and shallow-subsurface materials for use in a laboratory radar analysis program. The suitability of both naturally occurring and artificially prepared samples should be investigated for program use.

b. On the basis of data obtained in the current WESTAR program, methods of study and analysis be developed for the prediction of radar reradiation characteristics of specific materials and properties possibly representative of lunar surface and shallow subsurface conditions.

c. Prediction methods and theoretical radar potentialities developed in item (b) be tested in a radar simulation facility. Informal discussions with personnel of the U. S. Army Engineer Waterways Experiment Station, Vicksburg, Mississippi indicate that it may be possible to use the WESTAR facility for this work. The possibility of making formal arrangements should be explored. If suitable arrangements cannot be made for the use of WESTAR or similar facilities, the construction of a relatively simple far-field radar laboratory is recommended. Samples of naturally occurring terrestrial and "manufactured" materials possibly having lunar counterparts should be prepared and radar reradiation signatures of the samples obtained. Radar frequencies at or near X-band (3 cm) should be employed.

d. A program be planned and conducted to irradiate natural samples used in item (c) with simulated solar proton bombardment. Radar reradiation signatures of the proton bombarded samples should be obtained.

e. A program be planned for irradiating radar antennas with closely simulated solar radiation under a vacuum of at least 10^{-7} mm of Hg. The program should be conducted to determine if possible effects, such as secondary emission, would significantly alter propagation characteristics of radar antennas in the vicinity of the moon.

f. The availability of carbon dioxide absorption data in the microwave region be investigated. If such data are not available, the necessary experimental work should be planned and initiated.

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APPENDIX A

SELECTED QUOTATIONS ON THE LUNAR ENVIRONMENT

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A. TEMPERATURE

1. Extremes

a. Sun to Shade

The lunar surface temperature varies from +134° C in the sun to about -153° C in the shade (however this may be as low as -183° C due to measurement errors).

Wacholder, Fayer p. 7 (92)

120 - 400° K
-150 - 127° C
[assumed]

Ingrao, etal. (50)

b. Day to Night

All experimental work done so far point to the range of the temperature changes of the lunar day being in the enormous range of from 261° F to -279° F.

Barabashov (1)

The lunar surface temperature reaches a maximum of around 261° F at the subsolar point and drops to a nighttime value of approximately -243° F.

Buwalda (14)

The lunar surface temperature falls from a maximum of around 127° C at the subsolar point to a nighttime value of approximately -153° C. The temperature below the level of the diurnal variation in the ground is -23° C.

Jet Propulsion Laboratory p. 5 (106)

On the other hand, the poor resolution associated with the use of relatively long wavelengths means that the observed antenna temperatures

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[ ] Editor's Note
( ) Reference Numbers from Report Immediately Preceding this Appendix

are averages over a large part of the lunar disc. This complicates the comparison between the calculated and measured temperatures. It follows that any attempt at a detailed consideration of the lunar surface from the point of view of thermal radiation must await more precise experiments, and the conclusions reached here therefore, concern only the average characteristics of the surface materials.

Giraud p. 8 (37)

The inconsistancy of the lunation temperatures jeopardizes their interpretative value in defining the characteristics of the lunar surface material.

Tolbert p. 9 (84)

2. Work Status

It is evident that more theoretical as well as observational work is required to clear up these difficulties, i.e., thermal inertia inconsistancies, rates of cooling and surface roughness effects.
[temperature measurements at various wave lengths]

Sinton pp. 426, 427 (81)

3. Thermal Shocks

Thermal shock caused by a sudden temperature drop of 300° C is to be expected.

Wacholder, Fayer p 7 (92)

4. Subsurface

The most recent such measurements (radio measurements) by Meyger & Strassl, show a subsurface equilibrium temperature of -23° C which does not change with phase.

Salisbury p. 92 (73)

5. General

The 4.3 mm wavelength emission from large lunar areas, as resolved with an antenna beamwidth of approximately 0.1 degree, show the maria, in general, to reach a higher temperature and to vary over a wider range of temperature than do the continent areas.

Tolbert p. 1 (84)

B. SURFACE FEATURES

1. Small Scale

a. Existence

[No dust] Not ordinary diffusing surface in visible spectrum.

Fessenkov p. 125 (32)

It does not seem possible that the rapid cooling of the ground could, except for occasional fractures, lead to a systematic pulverization of the surface.

[experimental]

Dollfus p. 147 (20)

So far neither the existence nor even the possibility of UV rays and solar X-rays breaking down crystalline lattices has been proved.

Dollfus p. 146 (20)

It is probable that the yellowing observed in the olivine and alumina can be attributed to lattice damage.

[proton bombardment of dunite]

Hapke p. 31 (46)

These [obsidian, pumice, basalt, scoria] and all other species ot terrestrial rocks measured, failed to reproduce the [visual] lunar curve. The reasons are basically different for solid and powdered rocks. The solid rock surfaces simply do not possess a sufficiently complex macrostructure not even the porous slag-like scoria. In powdered form the opacity of the rock grains was too low. There is little doubt that, had the transparency of the grains been less, this surface [sifted rock grains] would surely have reproduced the lunar curve.

Hapke pp. 16, 77 (46)

The main effect of the bombardment [10 Kev proton gun] was the creation of the black magnetic oxide, Fe_3O_4, and probably also FeO [starting with Fe_2O_3]; the surface of the powder in the target area was completely blackened. In addition, along the edge of the boat where some isolated lumps of Fe_2O_3 had clung (but were still in the beam), iron whiskers were observed.

Hapke p. 26 (46)

Gold believes that the average depth of dust on the moon is 1 km and that the maria are, in fact, composed of dust rather than lava. Whipple, on the other hand, shows that some of material involved in high energy explosions will attain velocities greater than the velocity of escape from the moon and that the amount of material so lost may possibly exceed the amount accreted.

Salisbury p. 111 (73)

When lava comes out on the lunar surface, the gases absorbed into it must be discharged very violently due to the absence of any atmosphere. Hence we may expect to find spongy structures of the pumice type widespread on the moon. Under vacuum conditions such structures must have a very small heat conductivity which is 1/100th to 1/1000th that of solid terrestrial rocks.

[physical observations]

Kozyrev pp. 582, 583 (58)

It appears at this time, nevertheless, that the micro-relief is great, that the dust layer is thin, and that the dust is not loose and does not migrate.

Salisbury p. 113 (73)

Sytenskaya suggests that the magnitude of irregularities in the micro-relief could be narrowed down to a range of 0.1 mm to 0.1 m. Green believes that this range is reasonable.

Halajian p. 34 (45)

As yet we do not know to what degree dust covers the lunar surface nor its depth. We do not know if the exposed rocks are vesicular or surface-sintered. We do not know what kind of rocks exist there. It is the writer's opinion that volcanic extrusives exist, some vesicular, some not, of varying types covered at places with variable thicknesses of predominantly volcanic dust in different degrees of induration.

Green p. 15 (43)

b. Texture

[Dust] - covered with a very absorbing powder, having a constitution similar to that of volcanic ash, could be very thin, but apparently covers the entire surface. [polarization]

Dollfus pp. 144, 145 (20)

A suggestion was made by Gold that the surface of the moon is covered by fine dust produced by light erosion.

Urey (87)

Our conclusion concerning the thickness of the lunar dust layer can be summed up as follows: accretion of interplanetary dust has lead to a general deposition of about 50 cm. The transport of dust by electrostatic means can result in a layer thickness of 20 to 100 cm, with greater depths in shadow areas such as crevaces.

Singer & Walker p. 119 (80)

Surface covered by layer composed of extremely porous substance, containing separated grains capable of reflecting light backwards and casting shadows in their neighborhood. [photometrically]

Fessenkov p. 128 (32)

In summary, the experiments reported here strongly support the hypothesis that the upper few millimeters of the moon's surface consists of finely-divided rock dust. The particles of dust are between 1μ and 50μ in diameter (or are coagulated into dense clumps of this size), about 10μ being most probable. The average opacity of the minerals of this dust is higher than that of terrestrial rocks. Such darkening can be accounted for by the absence of quartz together with the effects of proton bombardment. The particles of dust build themselves into structures of low density and great intricacy by electrostatic forces and are probably not sintered or welded together to any great extent.

Hapke p. 40 (46)

The surface layer of the moon consists of loose particles that are approximately 0.3 mm in diameter and composed of material with high silica content. The hardness of the lunar surface ranges from that of soft wood to that of very hard rock.

Buwalda (14)

The surface layer of the moon consists of loose particles approximately 0.3 mm in diameter composed of material with high silica content which is a very good insulator. Thickness of the surface layer is between 1 and 10 cm. The material directly beneath the surface dust layer is not composed of loose particles, but is solid in nature. The nature of this solid may vary from a basaltic type of rock to a low density rock froth. This layer of material extends to considerable depth and determines the competence of the lunar surface.

Buwalda pp. 7, 8 (14)

Smooth areas of the lunar surface at a scale of the spacecraft or less consists of granular material, perhaps loosely sintered in parts, of grain size range 1 - 300 microns.

Jet Propulsion Laboratory p. 6 (106)

A low density (probably increasing with depth) and a loose structure. The expected range of granule sizes is between 10 and 300 microns.

Giraud (38)

Gold and Van Diggelen have suggested, on both theoretical and observatinnal grounds, that the crater floors may have a spongy texture of reduced density.

Pettengill p. 6 (67)

The early estimate of an unconsolidated dust layer many kms thick is believed to be too pessimistic today. A shallower layer of dust underlaid by a hard stratum is more widely accepted now. Some authors concede a deeper accumulation of dust in the valleys and lowlands. However, latest opinion on the nature of the lunar crust in this country and abroad is leaning toward a sintered froth model of low density.

Halajian p. 4 (45)

Apparently the dust particles in the lunar vacuum 'stick' to their place of origin except when they are distributed by meteoric impact, this could cause displacement on a very limited scale from mountain slopes to the valleys.

Halajian p. 34 (45)

The effect of solar wind in producing a lunar micro-relief has been discussed by Wehner, et al. On the basis of experimental data, forty meters of lunar surface material is assumed to have been eroded away by solar winds in a billion years. In this process, the light fraction of the material sputtered, escapes into space leaving a metal rich residue. Their experimental data support the assumption that loose material on the surface of the moon has been fused to form a solid but porous crust. [Based on summing up the sputtering yield for silver under a normal ion incidence of 5-Kev protons and 20-Kev He ions.]

A more realistic model would have been radiation, weighted 90-percent protons and 10-percent He ions, incident on silicates which is the most likely lunar surface material.

Green p. 12, 13 (43)

Wehner's simulation of solar wind bombardment on iron dust indicates that atoms that are sputtered and subsequently trapped could provide the glue which cold welds surface and underlying particles together.

Halajian p. 39 (45)

Sputtering effects are thought to modify only the uppermost few centimeters at most of the lunar surface.

Green p. 13 (43)

At the current state of our knowledge in particle physics and surface chemistry, it would be premature to speak of a sintered surface on the moon. However, the results of some recent studies and experiments suggest that long exposure to ultrahigh vacuum and radiation, such as exists on the moon, could be conducive to particle growth, or coarsening, and that further research in this field may well be worth the effort.

Halajian p. 30 (45)

Measurement of lunar radiation at wave lengths of 1.6, 3.2 and 9.6 cm suggest that the moons surface may be a porous material like pumice, based on its apparent thermal conductivity, Soviet Scientist V. S. Troitski reported.

Aviation Week and Space Technology p. 33 (104)

It can be concluded from the last three reported experiments that the surface of the moon is not densely covered with objects having sizes in the range of 2.5 meters to 10 cm.

Evans p. 457 (26)

It is not known at what wave length between 10 cm and 10^{-2} cm the transition occurs between smooth moon scattering and uniformly bright scattering. It seems unlikely that this information could be obtained [with earth based radar equipment] in view of the strong atmospheric absorption in this wave length range.

Evans p. 457 (26)

Previous estimate of a lunar grain size spectrum of 1 micron to 10 cm is judged possible, but emphasis on the abundance of finer particles is disputed. A coarser particle size distribution is advocated.

Halajian p. 39 (45)

Our deduction that the scale size of irregularities is on the order of one meter appears to agree with all the available published results from lunar echo experiments.

Von Biel p. 34 (91)

c. Composition

Barabashov - has established on the basis of spectro photometric observations of rock species found on the earth and moon that the lunar surface does not resemble a fused surface but comes closest to a disrupted tuffaceous rock interspersed with coarse-grained volcanic ash.

Halajian p. 4 (45)

Conditions under which soils could be formed on the moon and our knowledge of the physico-chemical properties of freshly produced surfaces suggest that the pulverization of a suitable magma rock in vacuo will come closer to preparing a realistic moon soil sample than the difficult and questionable separation of sorbed impurities from earth-soils.

Halajian p. 19 (45)

It seems probable that tektites are samples of the lunar crusts but in the absence of any conclusive proof of this, it appears best to assume a chondritic composition for the moon minus about 5% iron.

Salisbury p. 102 (73)

Consequently, [calculations in reference to earth] approximately 1 centimeter of meteor material is accreted onto the lunar surface every 100 million years. Since the beginning of Paleozoic times, nearly 5 cm of meteor dust has been deposited.

Brereton p. 9 (6)

An analysis by Jet Propulsion Laboratory [shows the] possible low and high concentrations of these elements on the lunar surface. Fe, Si, Mg, Al, O, K, Ca, Na, and Ni.

Stinner p. 8 (82)

Generally, it can be concluded that the surface [lunar] is composed mainly of about ten elements - oxygen, silicon, alumium, iron, magnesium, calcium, sodium, potassium, titanium, and nickel, - with minor amounts of the remaining elements.

Brereton p. 4 (8)

In this paper it was reported that the specular - like reflection by the lunar surface was similar to that observed with airborne radar over dry, sandy terrestrial deserts at normal incidence by Grant and Yaplee (1957).

Evans p. 455 (26)

Dielectric properties of the lunar surface indicate that it might be a mixture of 80% quartz sand with the balance consisting of rocks.

Aviation Week and Space Technology p. 33 (104)

A material in a somewhat degenerate state (possibly radiation damage).

Giraud (38)

The action of light and high energy particles has almost certainly produced a superficial layer of material different from any natural material on the earth's surface, so that studies of the polarization and absorption of light cannot be expected to identify the lunar surface materials. Sytenskaya (1957) has studied the brightness-color diagrams of the moon and many terrestrial materials and found no agreement between those of the moon and any terrestrial material. We may conclude that we have no definite evidence in regard to the chemical composition of the surface materials of the moon.

Urey p. 511 (88)

The possibility of the existence on the surface of the moon of minerals not occurring on the earth cannot be denied. After all, meteorites do contain minerals unkown on the earth and some authorities maintain that tektites actually originated on the moon. Practically all speculation on the nature of the surface of the moon has been based on the tacit assumption of similarity between terrestrial and lunar surface minerals. The lunar surface, perhaps at the very outset different from the surface of the earth, has been subjected to cosmic bombardment for millions of years in conditions of nearly perfect vacuum. This situation is certainly without analogy on the surface of the earth.

Bobrovnikoff pp. 98, 99 (4)

d. Structure

The depth of the surface layer, based on Pettengills data, could be as great as 10 km.

Brown (10)

The moon's surface is covered by a layer of loose dust about 3 ft. thick.

Buettner (13)

The surface of the moon as a whole may be covered with a few inches to a few feet of dust.

Salisbury (72)

It is also speculated that the structure of this top layer is of some peculiar nature.

Hayre, Moore pp. 203, 204 (47)

Lunar dust may be as hard as rock due to electrostatic attraction or have no bearing strength at all caused by mutual repulsion of the particles.

Salisbury (72)

The Russians are actively pursuing their radio-telescopic investigation of the moon. Their latest progress report refutes the existence of a continuous ocean of unconsolidated dust but indicates instead that the surface of the moon is made of a homogeneous, slag-like, hard porous mass comparable with cotton-wool and half as dense as water.

Halajian p. 35 (45)

Comparison of spectro-photometric observations of rock species found on the earth and the moon do not reveal any primary exposed rocks on the lunar surface but indicate instead, that the lunar surface is a product of later development.

Halajian p. 9 (45)

If only one-thousandth of the displaced material due to meteorite impact was ejected to a sufficient distance to settle uniformly over the whole of the moon, the thickness of this layer would be 25 mm.

Dollfus p. 148 (20)

The picture which thus emerges for the lunar surface is that of a layer, possibly very deep on low grounds and thin on the highlands.

Giraud (38)

Gibson uses a study of lunar thermal radiation during lunar cycles and eclipses to conclude that the surface structure of the moon consists of two or three consecutive layers, the uppermost is said to be possibly 0.5 cm deep and its material seems like sand in vacuo. The intermediate layer may be several cm or more in depth and has high electric conductivity; while the bottom layer seems to have indefinite depth and may have rocky structure.

Hayre, Moore p. 204 (47)

It can be tentatively concluded at this time that the subsurface structure of the lunar highlands should consist of a highly fractured basement rock overlaid by discontinuous layers of rubble, rock flour and meteoritic material. The subsurface structure of the marias should consist of a highly vesicular surface layer grading downward into solid lava, and disturbed only by scattered wrinkle ridges, rilles, domes, and late craters. The vesicles should reach a maximum size of 6 ft. in diameter and a maximum depth of 40 ft. Probable dimensions would be about one half of the maximum figures.

Salisbury p. 107 (73)

e. Physical Parameters

Thermal conductivity in the range of 10^{-4} cal/cm sec$^{\circ}$C.

Buwalda (14)

The investigation of radio emission by the lunar surface by Jaeger and Harper shows a possibility of an uppermost surface layer which may be 2 millimeters thick and whose heat conductivity is 1/100th of that of the next lower level.

Hayre, Moore p. 203 (47)

A plausible set of physical constants should include a dielectric constant between 1 and 1.5, a thermal conductivity of order 5×10^{-6} to 10^{-5} cal sec^{-1} cm^{-1} deg^{-1} and a volumetric specific heat of about 0.1 or 0.2 cal deg^{-1} cm^{-3}.

Giraud (38)

Average reflectivity	0.01 to 0.05
Average relative permeability	1.0
Average relative permittivity	1.2 to 1.4
Average depth of layer	several meters
Average density of layer	0.05 to 0.10 (silica)

Buwalda p. 5 (14)

The average albedo or reflecting power of the moon's surface is 0.07.

Brereton p. 2 (6)

The integrated reflected power [at 3.6 cm] yields a value for the radar cross section of the moon of 2 per cent of the physical cross section (πa^2). This is substantially lower than the average value obtained at meter wavelengths (7 per cent) and the only previous measurement at 3 cm (9 per cent). However, two published measurements at wavelengths close to 10 cm also indicate a cross section of 2 per cent. It is possible that all three low values result from undetected losses in the radar equipments employed, or that the reflection coefficient is substantially lower at these short wavelengths. This second possibility could well result from the presence of a thin layer of dust overlying most parts of the surface.

Evans p. 34 (25)

Results indicate [using bistatic CW] that the coefficient of reflectivity of the lunar surface is 7 per cent. Since this is in disagreement with the 2 per cent measured by Dr. J. V. Evans using monostatic backscatter, further measurements are being made.

Communications Group
of Lincoln Laboratory p. 5 (105)

It seems probable that the directivity (g) must be of the order of 1.3 ± 0.1 and hence the reflection coefficient $\rho \approx 0.06$ - the value 0.06 corresponds to a value for the dielectric constant K_1 of 2.72 which is close to the value observed for dry sandy soil.

Evans p. 470 (26)

From a power measurement alone, ϵ and S cannot be obtained explicitly, but if it is assumed that $\mu = \mu_o$ then $\epsilon = 9.6 \times 10^{-12}$ farads/m ($=1.1\,\epsilon o$) and $S = 3.4 \times 10^{-4}$ mhos/m. Both of these values are smaller than expected and few (if any) naturally occuring substances on earth, apart from liquids or gases, have a relative permittivity as low as 1.1. Although this is no reason for ruling out the possibility of an appropriate lunar substance, it may be of interest to observe that if μ is increased by a factor α, ϵ, and S are increased by the same amount. Taking α to be, for example, 1.4, we now have $\mu = 1.4\,\mu_o$, $\epsilon = 1.5\,\epsilon_o$, $S = 4.8 \times 10^{-4}$ mhos/m, and these are not inconsistant with soils such as magnetite.

Senior and Siegel p. 227 (76)

It is shown that the available data would predict a mean permittivity 8.2×10^{-12} farads/meter and a mean conductivity 4.3×10^{-4} mhos/meter.

Senior and Siegel p. 29 (75)

Mr. Vogler and fellow NBS scientists surmised that the moon's dry loose surface material necessitates a relative dielectric constant near unity and a very low conductivity; figures of 1.1 and 2.0 and 10^{-3} to 10^{-4} mhos/m, respectively, were assumed.

Electronics News p. 45 (99)

Observations of several distinct characteristics of moonlight all point to the same conclusion - namely, the existence of luminescent regions on the lunar surface.

[spectrometer]

Grainger & Ring p. 404 (42)

He [Whipple] also maintains that the lunar surface could not carry a strong electric charge because interplanetary space is a relatively good conductor (10^3 electrons/cm^3 near the surface).

Salisbury p. 111 (73)

Using more up-to-date data concerning the solar ultraviolet spectrum, Öpik and Singer derived a potential for the surface of the moon of about 20 - 40 volts positive.

Singer & Walker p. 7 (79)

Concurrently measurements have been made on tektites, meteorites and on those rocks which one theory or another would have predicted came from the moon or could be similar to lunar materials. Our results showed that, in the form which they are found on earth, these could not be the materials of the outer surface of the moon.

Brunschwig p. 2 (11)

The question may be asked whether in radar technique we have learned anything at all about the moon. Perhaps the various effects give us information about the structure of the ionosphere of the earth and not about the surface of the moon.

Bobrovnikoff p. 92 (4)

It can be seen that in general the brightest features display the greatest phase lag. This conclusion, if true, is a most peculiar property of lunar reflectivity which we do not know how to explain.
[photographic photometry]

Brown p. 3 (9)

2. Large Scale

a. Craters

1) Origin

a) Volcanic

Volcanism appears to have been spread over most of lunar history though apparently it has changed with time. Because of the spatial association of dark-halo craters with Copernicus and the very similar crater Theophilus, there is a suggestion that the later maar-producing volcanism was triggered by impact.

Shoemaker pp. 350, 351 (77)

It is no accident that the gases are given off precisely from the central peak of the crater Alphonsus. It is probable that the peak of this crater is a funnel, i.e., it is a genuine volcano.
[spectroscopy]

Kozyrev p. 383 (58)

Since we must invoke volcanic activity after all at least to explain the major features on the surface of the moon, the meteoric origin seems a superfluous hypothesis.

Bobrovnikoff p. 103 (4)

A much greater (than the earth) abundance of rock froths and a larger vesicle size is predicted for lunar surface extrusives.

Green p. 37 (43)

Three guesses concerning the nature of the rocks that make up the surface of the moon are (1) meteoritic materials, (2) volcanic extrusives, and (3) ultrabasic rocks, including serpentines.

Green p. 40 (43)

Present-day astronomical resolution is inadequate to settle the question of the impact or volcanic origin of the lunar surface.

Green p. 21 (43)

(b) Impact

There is one major feature of lunar craters observable from the earth that may permit unambiguous discrimination of impact craters from volcano craters. This feature is the distribution pattern of ejecta.

[nuclear blast data]

Shoemaker p. 324 (77)

2) Model Studies

Photometric model requires porous wells over 2/3 of the surface with depths much greater than widths.

Fessenkov p. 126 (32)

b. Slopes

Lunar slopes are not inclined more than a few degrees to the horizontal and large steep slopes (of 10° or more) of appreciable size appear to be conspicuous by their absence.

[Shadow method]

Kopal p. 275 (56)

The measurements show that rarely if ever on the moon's surface does the average slope exceed the relatively modest angle of 10 degrees.

Jastrow p. 6 (51)

[Speaking of the maria-like regions] slopes greater than 15 degrees will not be encountered.

Buwalda p. 4 (14)

The properties of the semispecular reflection from the moon may be described by means of a large scale irregular surface structure on the moon with slopes of the order of 1/20 to 1/10.

Hagfors (44)

It should be emphasized that, although the lunar surface is generally smoother than it appears, craters with diameters less than 50 km have a mean inner slope angle of 28°. The lunar surface relief therefore, is by no means negligible because craters of this size comprise the majority.

Salisbury p. 107 (73)

It has been found that smaller craters ranging up to 20 miles in diameter, are relatively deep (depth 10% of diameter). Larger craters, ranging up to 100 miles in diameter, are relatively shallow (depth 3 to 5% of diameter). Smaller craters also have steeper inner slopes (averaging about 33°) than larger craters (averaging about 12°).

Salisbury p. 13 (72)

Slopes inside the craters are an inverse function of size, the 10,000 ft diameter crater having a maximum slope of 28° while the 1000 ft diameter crater has a maximum slope of 46°.

Kornhauser p. 1 (57)

c. Water

However, on the moon there is no water, no appreciable atmosphere, and in fact there is no way in which to produce substantial changes of any kind on the surface.

Jastrow p. 2 (51)

Water, either solid or liquid could not exist on the moon for more than very short periods of time.

Urey (86)

While other components of the moon's atmosphere escape or are escaping to outer space, the water molecules created chemically by solar wind collect in the cold spots of permanent shadow where lunar glaciers up to 300 feet thick may have accumulated over the ages.

Öpik (64)

Water would be much more stable on the lunar surface than sulfur dioxide since it has an extremely low vapor pressure.

Watson, Murray, Brown (93)

Through solid-vapor kinetic relationships it has been shown that water is far more stable than the noble gases or other possible constituents of the lunar atmosphere. Calculations indicate that the amount of water lost from the moon since the formation of the present surface conditions is only a few grams per square centimeter of lunar surface.

Watson, Murray, Brown (94)

Thus, large deposits of water in some form are probably to be found beneath the chain craters and rilles, along with deposits of the other volatiles and any other elements they may have carried.

Salisbury p. 119 (73)

Water, in the form of ice, may be found in restricted polar localities in and around volcano orifices, or in deep craters and fissures. There is also a possibility that some water has formed at a depth of 1 or 2 meters below the lunar surface by the combination of solar hydrogen ions with the oxygen of lunar rocks.

Brereton p. 9 (8)

d. General

Undoubtedly there are differences - probably critical differences - in the physical, chemical and historical setting of the surface of the earth and moon.

Shoemaker p. 284 (77)

The highest mountains found on the surface of the moon - the Leibnitz and Doerfel mountains - are located in the limb regions near the south pole of our satellite; and their altitudes have recently been determined by Watts to 5970 and 5600 m, respectively. The highest lunar mountains attain, therefore, the altitudes of Kilimanjaro or Mount McKinley, but fall far short of those of the terrestrial Himalayan giants.

[shadow method]

Kopal p. 275 (56)

Generally speaking, the moon's crust differs from the earths by having no such sedimentary rocks as shale, sandstone, and limestone, which together form about 5% of the earth's crust, but 95% of the visible surface, and by being slightly more basic chemically.

Brereton p. 6 (8)

The minerals in the lunar igneous rocks should consist of the silicas, the feldspars, the feldspathoids, the pyroxenes, the amphiboles, olivines, the micas, apatite, titanium, and accessory minerals.

Brereton p. 7 (8)

For the polar base, such as on the Leibnitz Mountains, the optimum base site would be on a caldera. The crater floor should be eternal darkness and should contain mineralization possibly sulfur, boron, or the halogens. Basalt flows and pumice should be present on the crater flank.

Green p. 36 (43)

These [volcanic mineral deposits] can be expected to include concentrations of such volcanoid minerals as molysite, $FeCl_3$; sassolite, $B(OH)_3$; siderazot, Fe_5N_2; and cotunnite, $PbCl_2$.

Brereton p. 7 (8)

Meteoritic material will veneer a large part of the lunar surface - the chief mineral constituents of meteorites are nickel-iron, olivine, rhombic pyroxene (enstatite, bronzite, hypersthene), monoclinic pyroxene (augite, diopside, clenohypersthene), and feldspar (both plagioclase and orthoclase). Minor amounts of schreibersite (iron-nickel phosphide), troilite (ferrous sulfide), cohenite (Fe_3C), graphite, chromite, and tridymite are usually present.

Brereton p. 8 (8)

Our knowledge of these rills or cracks on the surface of the moon is, therefore, almost wholly based on visual observations with all their attendent uncertainties. Much the same can be said of rapid changes in the color and brightness of the various details on the moon. The existence of such changes seems to be beyond doubt in spite of the fact that they have never been recorded on photographs.

Bobrovnikoff p. 4 (4)

C. ATMOSPHERE

1. Existence

The lunar atmosphere is a vacuum.

Buwalda (14)

No permanent atmosphere can exist on the moon. There are several mechanisms by which this atmosphere can escape: thermal, ionic, and collision with solar winds.

Öpik (64)

The most probable explanation of this result is as follows: gases consisting of complex molecules giving off a faint emission were released from the central peak of Alphonsus.

[spectroscopy]

Kozyrev p. 371 (58)

Several sources of the gases, krypton and xenon, (thought to be too heavy to escape from the moon atmosphere) were evaluated. The sources are spontaneous fission of U-238, fission of U-235 by thermal neutrons from cosmic rays, thermal fission of U-235 by an alpha-neutron reaction, xenon produced during the formation of the elements, and primeval gases trapped in rock.

Edwards and Borst (21)

[Atmospheric effects in the vicinity of the moon] It is clear that this effect [enhancement of solar radio emission during eclipse] whatever its explanation, is sometimes present and sometimes absent at the same wavelength, and does not exceed 15%.

Bobrovnikoff p. 90 (4)

Two other probable sources of a lunar atmosphere are the production of argon by the radioactive decay of potassium and the production of sulphurdioxide, carbon dioxide and water by residual volcanic activity. Solar wind would play a major part in reducing the density of the lunar atmosphere. Solar wind is usually assumed to consist of protons with a number density of $10^3/cm^3$ and a velocity of 10^8 cm/sec. In any elastic collision with an atom these protons will transfer an amount of kinetic energy sufficient for the escape of the atom.

Herring and Licht (48)

2. Density

The theory of this refraction [suggested explanation for enhanced solar radio emission] was worked out by Gurzadyan with the result that the density of the lunar atmosphere is 10^{-5} of the density of the atmosphere of the earth at sea level assuming the same chemical composition for both atmospheres.

Bobrovnikoff p. 90 (4)

It appears quite certain that the permanent atmosphere of the moon must have density not exceeding that of 10^{-12} of the pressure in the atmosphere of the earth at sea level. The only atmosphere that the moon may have with the pressure exceeding 10^{-12} is the local atmosphere.

Bobrovnikoff p. 105 (4)

The permanent atmosphere of the moon - if any - must contain less than 10^{10} molecules/cm^3 and is extraordinarily rarefied.

[polarized light]

Dollfus p. 158 (20)

In interplanetary space near the earth's orbit, Beard (1959) calculates a concentration of 10^{-15} particle/cm^3 for a size larger than a few microns. The concentration distribution varies as the inverse 7/2 power of particle radius, and as the inverse 3/2 power of the distance to the sun. The earth's gravitational field may increase the numbers in the immediate vicinity of the earth by as much as 10^3 to give a value for the flux at the top of the earth's atmosphere as high as 10^{-6} particles/cm^2-sec which is in agreement with the satellite data.

Vedder pp. 97, 98 (89)

There would, perhaps, be a reduction of 1000 between the earth's upper atmospheric micrometeorite flux density and that around the moon.

Johnson (113)

[Crater formation at hypervelocity] On the whole, only particles in the micron size range which have masses less than 10^{-4} g are likely to be encountered with any significant frequency [in free space]. The meteoroid velocity range is fairly well defined; essentially all meteoroids are expected to have velocities between 11 and 70 km/sec.

Eichelberger and Gehring p. 1583 (22)

3. Composition

Its [the lunar] surface is presumed to be dry and light and free of ionized atmospheric layers.

Electronic News p. 45 (99)

Gold has pointed out that the vicinity of the moon must contain thermal hydrogen gas at the temperature of the lunar surface and at a density greater than that of the solar wind by a factor of several hundred.

Gould p. 1 (39)

Although there is the possibility that enough gas is trapped in the crust of the moon to cause a steady leakage of this gas, these heavier gases might stay on the surface for awhile, providing a very tenuous but constantly replenished atmosphere.

Kellogg (55)

Some radiogenic krypton and xenon, as well as such radiogenic gases as argon, radon and helium should be continually released from the interior, while trace amounts of xenon, helium, neon, and argon will be produced by cosmic ray bombardment of the surface. In addition occluded gases will be liberated upon the impact and vaporization of meteorites, and some water and mercury vapor will be released during the slow vaporization of possible relict solid phases present in perpetually shadowed zones. It seems probable, however, that water vapor will be the major constituent.

Salisbury p. 91, 92 (73)

Violent dust storms from micrometeorites slamming into the lunar surface may be a serious hazard for man when he gets to the moon.

Science News Letter p. 277 (98)

4. Pressure

Pressure at the lunar surface is smaller than 0.05 mm Hg.

Urey p. 511 (88)

Atmospheric pressure may be as low as 6×10^{-13} earth atmosphere.

Wacholder, Fayer p. 7 (92)

The degree of vacuum on the moon has been estimated at from 0.076 mm Hg to 1.52×10^{-10} mm Hg (or the vacuum of interplanetary space — 10^3 particles per cubic centimeter).

Geer p. 2 (35)

For design consideration, the atmospheric pressure on the lunar surface can be assumed to be 10^{-12} mm of mercury.

Jet Propulsion Laboratory p. 5 (106)

Estimates of the lunar atmosphere vary from 10^{-12} to 10^{-16} torr. [Torr is defined as the pressure necessary to support a column of mercury one millimeter high.]

Halajian p. 15 (45)

5. Electrical Characteristics

Six arguments against a lunar ionosphere and net charges are as follows:

The observed values of ρ g [where ρ = reflection coefficient and g = directivity] are all a factor of 10 too small.

Some variation of the ionization density might be expected to occur with the variation of the phase of the moon. Thus at certain wavelengths, the density would drop below the critical value. No marked variations in mean echo intensity have been observed over the lunar month.

An extremely high electron density ($\sim 10^{11}/cm^3$) would be required to explain the results at 10 cm.

To explain the observed fading characteristics, the ionization would be required to follow the surface contours very closely. In this case the surface would appear little different from that which would be seen in the absence of ionization, with the exception that ρ would be unity.

The arguments advanced by Hargreaves show that it is unnecessary to postulate anything unusual about the lunar surface to explain the results satisfactorily.

If a dense lunar ionosphere were to exist then the microwave observations of the temperature of the lunar surface ought to show a much greater wavelength dependence than is observed, since the temperatures measured would be of the sky brightness reflected in this ionosphere, and not of the actual surface.

Evans p. 477 (26)

The absence of an ionosphere or radio-wave-reflecting region in the lunar atmosphere will present communication difficulties for exploration, scientific, and military personnel dispersed over the moon's surface. Radio communication between ground parties will be limited to the line of sight, and the irregular topography and greater curvature of the lunar surface will restrict this conventional communication technique to use within narrower limits than on the earth.

Brereton p. 16 (7)

The possibility that the moon possesses a critically dense ionosphere must not be overlooked, but it would appear from radio star occultation measurements that the lunar ionosphere does not have a density greater than 10^4 electrons cm^{-3} therefore the critical frequency for the lunar ionosphere is probably not greater than 1 Mc/s.

[10 Mc/s for earth]

Evans p. 431 (26)

If there is any trace of an atmosphere on the moon, it would be highly ionized and would be a good conductor to permit the buildup of a measurable electrostatic field.

Kellogg (53)

Radar calculations indicate an electron density near the moon of the order of 10^3 electrons/m^3.

Wacholder, Fayer (92)

There are difficulties in estimating the chemical composition, temperature, and, hence, the scale height of the lunar atmosphere, but if it is assumed that the temperature of the atmosphere is not very different from that of the sunlit surface (380°K), the scale height of a 'permanent' lunar atmosphere would be about 50 km and the electron density required to produce the observed angle of refraction is $10^3/cm^3$. A similar value is obtained if the atmosphere is not permanent but consists of gases that are continuously escaping and that are being replaced at the moon's surface. (I must point out that the 10^3 electrons per cubic cm measured is the excess over that in the surrounding medium.)

Elsmore pp. 47, 49 (24)

In the vicinity of the moon, electron densities may reach the value of 10^6 or 10^7 per cubic centimeter, which would certainly affect communications in this region.

Wacholder, Fayer p. 35 (92)

For large bodies the space charge density of photoelectrons becomes quite large; in the case of the moon it reaches a value of the order of 10^3 to 10^4 electrons/cm^3 just above the lunar surface.

Singer, Walker (79)

Interplanetary gas falls on the moon in streams from the solar corona and encounters the moon at velocities of the order of 1000 km/sec.

Wacholder, Fayer p. 7 (92)

Corpuscular radiation may have an influx of 10^{10} protons per cm^2 sec (this may vary by a factor of 10).

Wacholder, Fayer p. 7 (92)

The particulate radiation is believed to be variable, possibly with heavy primary cosmic rays and dangerous periods of radiation during solar-flare activity.

Geer p. 54 (35)

A solar radiation level of 2 cal cm^{-2} min^{-1} distributed by wavelengths as a $6000^{\circ}K$ black body may be assumed.

Jet Propulsion Laboratory p. 5 (106)

Primary cosmic rays: 0.27 particles cm^{-2} sec^{-1} $sterad^{-1}$ with energy greater than 150 mev with composition; 83% protons (mean energy 550 mev), 15% alpha particles (mean energy 2.2 bev), 2% heavy nuclei. Flux may vary by a factor of 2 during an eleven year solar cycle and by 10-20% during a few days.

Jet Propulsion Laboratory p. 1 (106)

Solar Flares: In general, events which produce large integral fluxes also generate higher energy particles than do smaller events. The solar particle radiation consists of protons, alphas heavier nuclei, and possibly electrons and neutrons at some times. The ratio of protons to alphas varies from 2 to 32 in different events.

During solar maximum small and medium events generating particles up to 1 bev occur on the order of once per month.

Very large events, with particles over 1 bev energy have occurred in the order of one in two years without observable clustering in any particular part of the solar cycle.

In the second largest of these big events (November, 1960) there was a flux of protons (30 mev) of 20,000 particles/cm^2 sec.

Secondary radiation generated in the moon's surface by the solar flare particles will increase, but will not exceed 0.2×10^4 neutrons cm^{-2} sec^{-1} and will probably be much less.

Jet Propulsion Laboratory p. 3 (106)

More recent data on the spectrum of the Zodiacal light and a re-evaluation of the mechanisms of interaction of the solar plasma with comet tails led to numbers more like 30 cm^{-3} (ion density) and 300 km/sec (stream velocity).

Neugebauer p. 5 (63)

However, measurements by Blackwell on the Zodiacal light indicate that the density of the electron component of the solar wind is less than 50 electrons/cm^3.

White & Wyller p. 9 (95)

It seems likely that the moon as a whole is positively charged at about twenty volts due to the intensity of solar ultraviolet radiation. Hence in the moon's vicinity there will exist a strong electrostatic field.

Öpik & Singer (65, 78)

An electrical phenomenon similar to silent discharge is responsible for some of the glows reported on the moon. High local charges may accumulate on the moon, since poor conductors of heat are also poor conductors of electricity.

Firsoff (34)

The amount of external noise received by an antenna located on the moon can be only roughly estimated. It is likely that the predominant source will be galactic; however, consideration also should be given to solar noise and noise arising from nearby earth. It is probable that noticable effects generally will occur only at the lower frequencies, except during periods of extreme solar activity when considerable noise at all frequencies may be expected.

The antenna circuit noise figure f_c, depending as it does on the antenna loss and absolute temperature of the antenna, will vary according to the type of antenna used, the elements of the circuit, and whether the antenna is in direct sunlight or not.

Vogler pp. 13, 14 (90)

D. MAGNETIC FIELD

1. Estimates

Recent Russian experiments indicate a lunar magnetic field of about 50-100 gamma.

[10^{-5} gauss = 1 gamma]

Wacholder, Fayer (92)

The magnetic field is probably no more than 0.05 that of the earth.

Geer (35)

At the present time we have no definite evidence that the moon had a magnetic field.

Kellogg (53)

2. Measurements

Following their recent moon-impact, scientists of the U.S.S.R. reported that their magnetometer in their space vehicle had not detected any evidence of a lunar magnetic field even though their instrument was capable of detecting fields down to 6×10^{-4} gauss.

Neugebauer (62)

If it is true (as seems likely from theoretical consideratinns) that the moon has no magnetic field of its own, it will still be affected by interplanetary fields. Preliminary results of the Pioneer V magnetometer experiment indicate that the intensity of the steady-state general interplanetary field is about 2.5 gammas, while transitory fields frozen into solar plasmas ejected from the sun reach a maximum intensity of abait 40 gammas in the vicinity of the moon.

Salisbury p. 102 (73)

E. DIMENSIONS

Mean distance from earth - 239,000 miles
Diameter - 2162 miles, 1/4 diameter of earth
Volume - 1/50 volume of earth
Mass - 1/83 mass of earth
Density - 3/5 density of earth
Surface gravity - 1/6 gravity of earth

Salisbury (72)

Distance to the moon varies from 210,000 miles to 245,000 miles.

Jastrow p. 4 (51)

APPENDIX B

FACILITIES SURVEY

APPENDIX B

FACILITIES SURVEY

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APPENDIX B

FACILITIES SURVEY

A. INTRODUCTION

This survey was designed to identify existing and proposed facilities that might be used in simulating radar analysis of possible lunar surface materials. "Lunar" facilities usually simulate only a few selected environmental factors and those affecting radar analysis are often omitted. Consequently, to the extent that time permitted, information was collected on all space-simulation, test and radar facilities that might be used either as they exist or with some modification. This appendix provides data concerning these facilities.

B. LUNAR SIMULATION REQUIREMENTS

An analysis or investigation of test facilities for any purpose must be prefaced by consideration of pertinent requirements.

Sections II and III of this report have considered the environmental requirements associated with simulated radar analysis of the moon. Analysis has shown that the atmospheric factors which must be considered are those listed below in Table B-1. They are listed in their approximate order of importance but their absolute degradation (or affect) has not influenced inclusion in this appendix, i.e., it was assumed that any one or all of these factors might have to be simulated.

An additional point that bears emphasis is that a suitable facility must be capable of allowing actual radar operation. To illustrate some of the implications of this statement, anechoic chambers (at radar frequencies) must be considered, facility dimensions must be adequate for radar operation, and facilities already complete with radar assume greater importance.

C. SIMULATION FACILITIES SURVEY

Selecting simulation facilities will evolve through considering the questions:

What facilities are currently in existence or are being planned? and

How adequate are these facilities for simulating radar analysis of the moon?

Many thousands of dollars and engineering man hours have been expended in creating lunar environment simulation chambers. Many are tailored to specific requirements and some are capable of satisfying a wide range of requirements. None, however, meet the total requirements established by this report.

1. Existing or Proposed Facilities

The simulation facilities listed in Tables B-2, B-3, B-4 and B-5 are those which appear to be most adaptable to lunar environment simulation for radar operations. These lists do not, by any means, include all adaptable existing or proposed simulation facilities, but provide a representative cross section. In Table B-2 facilities are listed by vacuum capabilities and by size. Table B-4 lists radiation simulation test facilities excluding visible and near-visible solar radiation facilities, which are noted in Table B-2. Tables B-3 and B-5 list high-temperature facilities and special equipment test facilities, respectively.

2. Examples of Three Types of Facilities

a. Small-Scale Simulation Facility

Figure B-1 shows a typical bell-jar vacuum test facility. This facility is located in the Flight Control Laboratory, Aeronautical Systems Division, Wright-Patterson AFB, Akron, Ohio.[35] This type of facility could be used if reliable radar scaling (i.e., scaling up radar frequencies and extrapolating results to lower frequencies) were possible for terrain analysis tasks.

b. Medium-Scale Radar Facility

Figure B-2 shows the WESTAR radar laboratory located at the U. S. Army Engineer Waterways Experiment Station in Vicksburg, Mississippi.[29] Modification of this type of facility could be accomplished by merely enclosing the soils cart within a lunar environment chamber through which radar can propagate.

c. Large-Scale Space Simulation Facility

Figure B-3 is an artist's sketch of a large-scale simulation facility[96] which could enclose a "lunar soil sample" and radar hardware.

TABLE B-1

LUNAR ENVIRONMENT SIMULATION REQUIREMENTS

Variable	Range of Requirement	Type
1. Vacuum	(60) 10^{-7} to (45) 10^{-16} mm Hg	Not applicable
2. Temperature		
Materials	(92) $90^{o}K$ to (92) $407^{o}K$	Not applicable
Atmospheric Gases	(52) 1300 to (52) 1500^{o} K	Not applicable
3. Gases	(20) Generally < 10^{10} molecules/cm^{3}*	Water vapor Sulfur dioxide Carbon dioxide
4. Aerosols	Not known.	Probably all postulated lunar materials of various diameters and particle densities.
5. Radiation**	(19) Up to 1000 Bev	Electrons, protons, ions, alpha particles, etc. (complete solar radiation)***
6. Ionization	(92) $10^{3}/m^{3}$ to (92) $10^{7}/cm^{3}$	Electrons
7. Magnetic Field	(73) 2.5 to (35) 3000 γ	Orientation unknown.

* Except for possible transitory periods when this might be exceeded, e.g., volcanic activity.

** This is radiation other than in the infrared spectrum or lower, to differentiate it from temperature.

*** The actual type and energy level, and density of such radiation can be varied. For example, the actual proton bombardment on the lunar surface is thought to be between 10^{8} and 10^{12} protons/cm^{2} sec. However, this may be increased to simulate radiation of materials over some long period of time on the lunar surface. If, on the other hand, antennae are being bombarded, the radiation expected in the lunar environment should be simulated as closely as possible to take into account recombination rates, etc.

TABLE B-2

VACUUM TEST FACILITIES [71]*

Pressure (mm Hg)	Facility	Size (ft)	Shape	Temperature	Availability	Remarks
$< 10^{-15}$	National Research Corporation Cambridge, Mass.[100]	3 x 7 UHV 1-1/2 x 3-1/2 XHV	Cylindrical	-422°F -322°F		Present measure limited to 10^{-11}
10^{-9}	General Electric	32 x 54	Cylindrical	-	-	
	NASA - Marshall Space Flight Center	12 x 30	Cylindrical	-	-	
	Grumman Aircraft	4 x 8.3	Cylindrical	To 500°F	-	Sample size - 44 x 100" currently used for soil testing.
	Bendix - Ann Arbor	4 x 8	Cylindrical	-400 to +2000°F	-	
	McDonnell Aircraft	3.5 x 8.3	Cylindrical	40 to 3500°F	-	
	Northrop Corporation - Norair Div.	2.5 x 5	Cylindrical	To 320°F	-	
10^{-8}	AEDC-ARDC-Arnold Air Force Station (Mark II)	200	Spherical	T = 100°K	To Ind. w/ AF reg.	Vibration solar radiation albedo.
	AEDC-ARDC-Arnold Air Force Station (Mark I)	42 x 82	Cylindrical	T = 72°K		
	NASA-Goddard Space Flight Center	35 x 65	Cylindrical			
	Lockheed Missiles and Space Company	18 x 20	Cylindrical	500°F Max 113°K Min	To Govt.	Solar radiation testing low temperature
	North American Aviation - Los Angeles	15 x 22	Cylindrical	Ambient		
	Fairchild Camera and Instrument Corp.[108]	14 x 15 x 13	Rectangular	-100 to +200°F		Vibration Solar radiation
	General Dynamics - Convair Division	4.8 x 10	Cylindrical	-300 to 2500°F		Mechanical feedthrough
	Goodyear Aircraft	1.5 x 2.5	Cylindrical			UV simulation
10^{-7}	NASA, Lewis Research Center	15 x 60 25 x 30	Cylindrical Cylindrical			
	Bendix Corp - Systems Div. Ann Arbor	20 x 27	Cylindrical			Solar simulation
	ASD - Wright Patterson AFB	8 x 25	Cylindrical			
	Chance Vought Corp - Dallas	10 x 10	Cylindrical		Ind - Yes Govt - Yes	Solar simulation Specimen orientation, 2 - axis.
	Douglas Aircraft - Santa Monica	5 x 5 x 5	Cubic	-100 to +500°F		
	Boeing-Transport Division	6 x 6	Bell			Bell Jar
	Goodyear Aircraft - Akron	1.5 x 2.5	Bell	-150 to 1500°F		Consolidated Vacuum Corporation Bell Jars
10^{-6}	AEDC-ARDC-Arnold Air Force Station	50 x 75	Cylindrical	To 100°K		
	NASA - Jet Propulsion Laboratory	25 x 25 (40)	Cylindrical			
	Northrop Corp. - Norair Division	25 x 37	Cylindrical	-32 to 70°F		
	U. S. Army[96]	32.8	Spherical			Proposed
	Litton Industries - Electronics Equipment Div.	8 x 15	Cylindrical	To 78°K		External radiant heat source. Habitable
	Lockheed Missiles and Space Company	4 x 4 x 4	Cubical	-65 to 1000°F		
	Bell Aerosystems	1.5 x 2.5	Bell			Bell Jar
10^{-5}	NASA - J.P.L.	6 x 7	Cylindrical	To 75°K	Generally No	
	Lockheed Missiles and Space Company	5 x 6	Cylindrical			
	Boeing - Transport Div. Seattle	3.5 x 5	Cylindrical	0 to 2000°F	Yes, dependent upon schedule	
	Aeronautical Systems Division	4 x 4	Cylindrical			
	North American Aviation Los Angeles					
10^{-4}	McDonnell Aircraft	14 x 14 x 20	Rectangular			

7.8×10^2	WESTAR - Vicksburg, Mississippi[29]**	50' arch	Arch	Ambient	Yes	Soils testing via radar (K_a-, X-, C- and P-band)

* These data compiled from Reference 71 except where noted.
** Not a vacuum facility.

TABLE B-3

SUMMARY OF HIGH TEMPERATURE TEST FACILITIES[71]

Facility	Temperature Range	Heat Flux BTU/ft^2/sec	Power Requirements	Specimen Size	Remarks
Aeronautical Systems Division	3000°F	200	50,000 kva	Large vehicles	Chamber size - 251 by 170 by 86 ft
Applied Physics Lab - Johns Hopkins University	Room temp to 3000°F in about 20 sec	--	150 kw	6 ft - length	Quartz lamps
Applied Physics Lab - Johns Hopkins University	Room temp to 3000°F in about 20 sec	--	750 kw	15 ft - length	Quartz lamps
Avco - RAD Div - Wilmington, Mass.	3800 to 5700°F	--	Rocket engine	2-1/2 - 4 in. dia.	--
Avco - RAD Div - Wilmington, Mass.	--	20 - 1200	--	3/4-in. dia right circular cylinder	Plasma generator
Avco - RAD Div - Wilmington, Mass.	2000°F	30 - 100	2100 kw	To 50 sq ft	Tubular, quartz, infrared lamps
Beech Aircraft	--	--	10,000 kva	--	Radiant heat lamps
Bell Aerosystems	8000 to 18,000°F	--	4 - 10 kw	1/4-in dia.	Plasma jet
Bell Aerosystems	0 to 2500°F	0 - 120	500 kw	3 sq ft	Quartz lamps
Boeing - Transport Div - Seattle	1000 to 4100°F	--	--	--	Work area - 1 by 2 by 4 ft (to 400,000 ft)
Boeing - Transport Div - Seattle	3000°F	--	6000 kva	--	Quartz lamps

TABLE B-3 (CONTINUED)

Facility	Temperature Range	Heat Flux BTU/ft^2/sec	Power Requirements	Specimen Size	Remarks
Boeing - Transport Div. Seattle	--	0 - 1300	--	--	Plasma jet
Douglas Aircraft - Santa Monica	5,000 to 25,000°K	0 - 4000	160 kw	3/4-in. dia.	Plasma jet, velocity (Mach 5)
Douglas Aircraft - Santa Monica	2500 to 4000°F	--	--	1-1/4 by 6-1/2 in.	Ceramic heat exchanger.
Douglas Aircraft - Santa Monica	3000°F	--	1400 kw	--	Quartz lamps
General Dynamics - Convair Div - San Diego	-100 to 3000°F	0-150	6000 kva	--	Quartz lamps
General Dynamics - Fort Worth Div	4000°F	--	30 kw	40-in. dia	Vacuum furnace
General Dynamics - Fort Worth Div	To 3000°F	--	7500 kw	14 sq ft	Quartz lamps
General Dynamics - Pomona Div	To 10,000°K	--	--	--	Plasma jet
Goodyear Aircraft - Akron	To 12,000°R	500	2 megawatts	2.5-in. dia.	Arc heated wind tunnel - Mach 3 nozzle. Heat flux on max model size at design operating condition.
Martin Marietta - Orlando	3000°F	--	75 kva	--	Infrared lamps
McDonnell Aircraft	-90 to 3000° F	0 - 200	12,500 kva	--	Radiant heat

TABLE B-3 (CONTINUED)

Facility	Temperature Range	Heat Flux BTU/ft^2/sec	Power Requirements	Specimen Size	Remarks
McDonnell Aircraft	--	--	500 kw	--	Hyperthermal plasma tunnel
McDonnell Aircraft	--	To 1500	--	3-in. dia.	Plasma generator
North American Aviation - Columbus	20,000^{o}F	--	--	--	Plasma jet
(North American Aviation - Columbus)	-450^o F to 2000^{o}F	--	--	16 ft dia by 40 ft long	Cryogenics and quartz
Republic Aviation	25,000^{o}R	--	720/1030 kw	1-1/2 in.	Arc heated jet
Republic Aviation	3000^{o}F	0 - 120	1500 kva	200 sq ft	Quartz lamps
	Re-entry	--	1000 kw	4 - 6 in.	Arc plasma generator; Enthalpy 18,000 BTU/lb; Stag. press. to 500 psia.

TABLE B-4

RADIATION SIMULATION TEST FACILITIES[71]

Facility	Neutron Radiation	Gamma Radiation	Critical Assembly Areas	Hot Cells	Size	Remarks
ASD - Wright Patterson	X	X	X	X	5'4" x 6'8" x 10'	Nuclear energy test facility.
Battelle Memorial Institute	X	X	X	X		Nuclear radiation test facility.
Boeing Transport Div. - Seattle		X			30'x 15'x 8'	Nuclear radiation test facility.
General Dynamics Ft. Worth Div.	X	X	X	X	30'x 20'x7'	Radiation effects facility.
Marquardt Corp.	X	X	X	X		Radiation effects laboratory.
Northrop Corp. Norair Div.	X	X		X	8'x10' x8'	Nuclear radiation facility.
Republic Aviation		X		X	8'x 15'6" x4'	Nuclear radiation cells.

TABLE B-5

SUMMARY OF SPECIAL EQUIPMENT TEST FACILITIES[71]

Company	Type of Facility	Remarks
Avco - RAD Division Wilmington, Massachusetts	Electron beam X-ray effect simulator	Study of the chemical kinetics of blow-off material resulting when an ablative type vehicle is irradiated by a high altitude nuclear blast
Avco - RAD Division Wilmington, Massachusetts	Light gas gun caliber 0.600/ 0.800 and test chamber (10-ft diameter x 12-ft long)	Study of electrical properties of wakes produced by ballistic projectiles
Avco - RAD Division Wilmington, Massachusetts	Ballistics range facility	Study of particle impact, wake properties, and gun development
Avco - RAD Division Wilmington, Massachusetts	Noise and field intensity meter	Measures level of RF noise originating in electrical or electronic equipment and for determination of the intensity of electrical fields
Avco - RAD Division Wilmington, Massachusetts	Microwave anechoic test facility	Measurement of the radar cross section of various targets and for determining antenna radiation patterns
Douglas Aircraft - Santa Monica	Antenna pattern ranges	Microwave near field measurement
Lockheed - Georgia Company	Cryogenic	Liquid hydrogen: $-423^{\circ}F$, 5000 gallon storage tank Liquid nitrogen: $-320^{\circ}F$, 1000 gallon storage tank
Lockheed - Georgia Company	Avionics laboratory	Microwave far field measurement
Republic Aviation	Microwave Anechoic chamber	Free space simulation

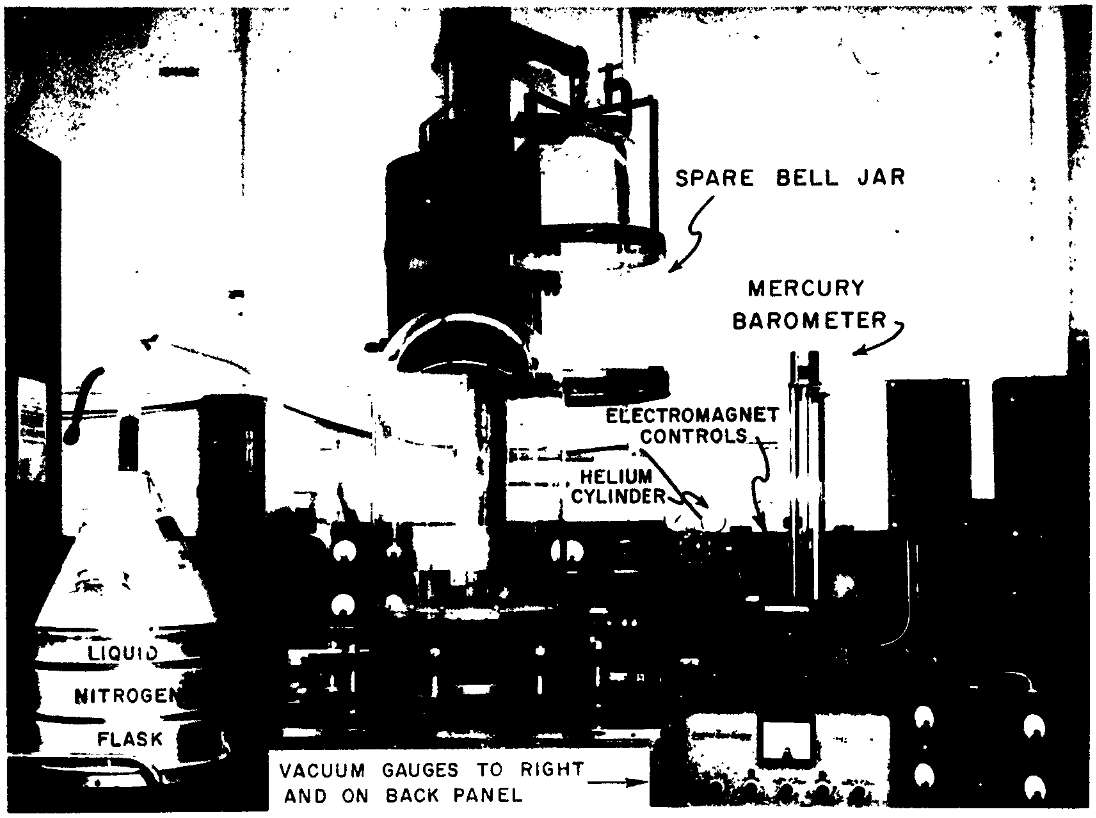

Figure B-1. Typical Bell-Jar Vacuum Test Facility

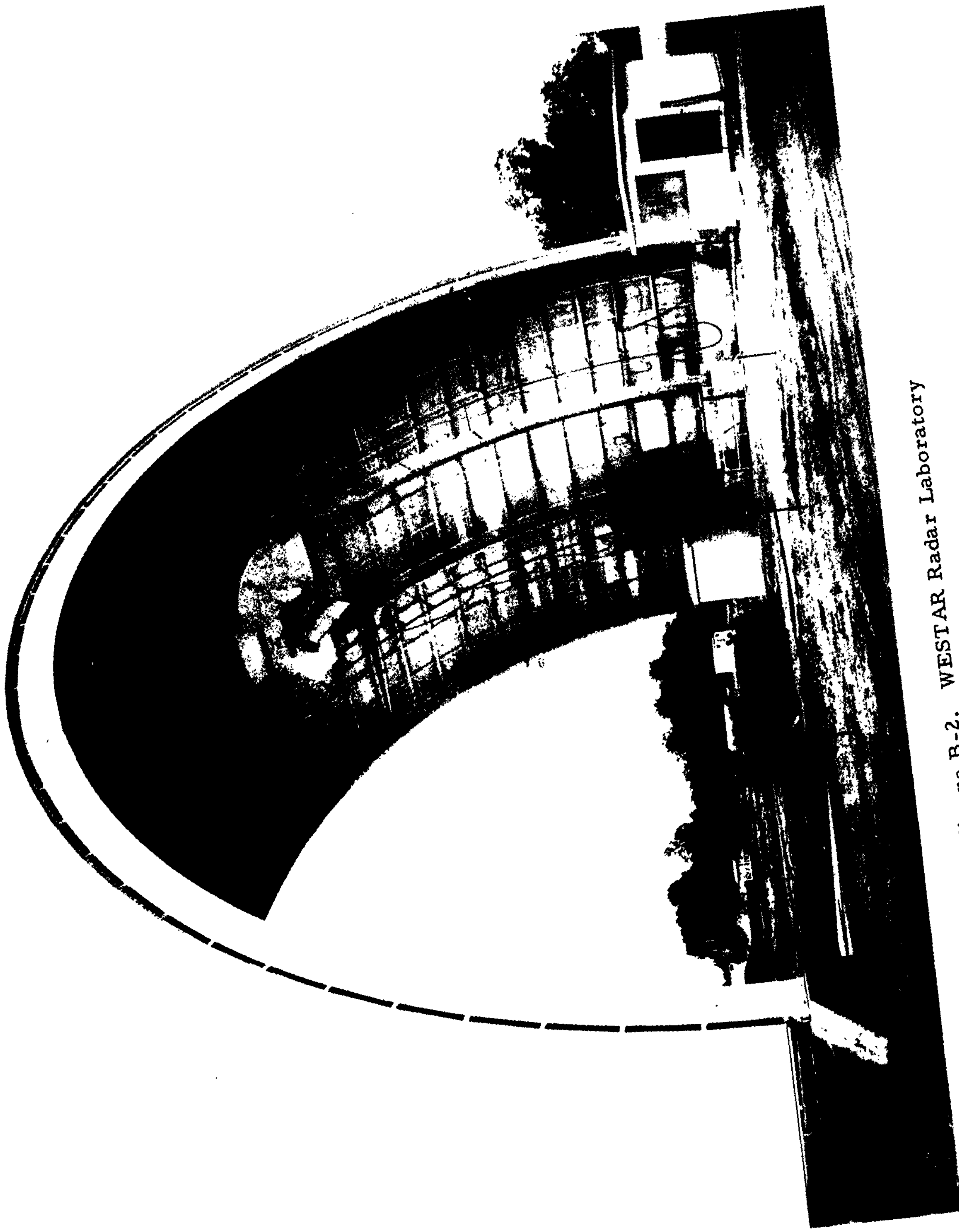

Figure B-2. WESTAR Radar Laboratory

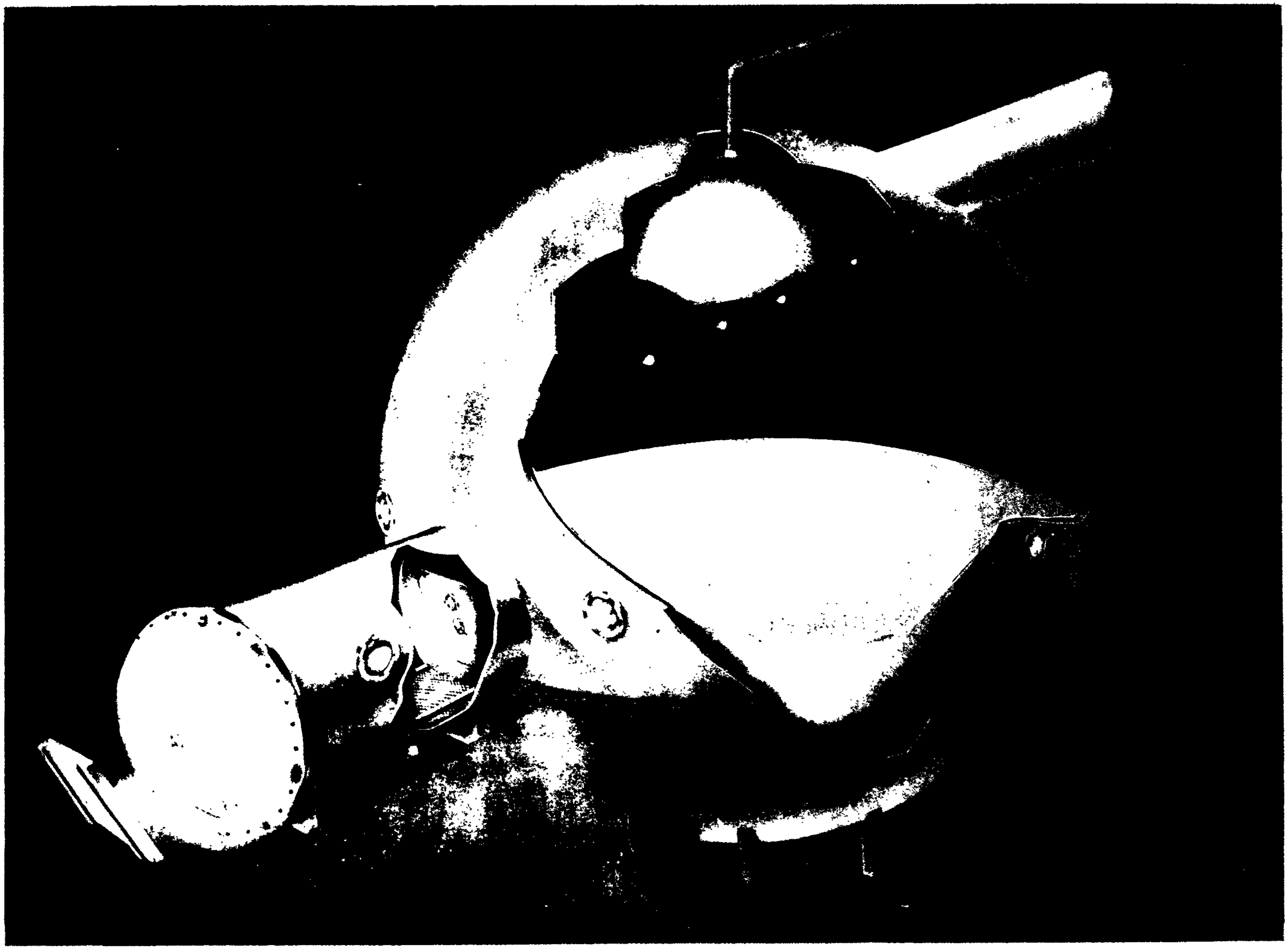

Figure B-3. Sketch of Large Scale Simulation Facility

Air Force Cambridge Research Laboratories, Laurence G. Hanscom Field, Bedford, Mass.
Rpt. No. AFCRL-62-1120. RADAR ANALYSIS OF THE MOON, PHASE I: FEASIBILITY OF LABORATORY SIMULATION. Final Report, 30 November 1962, 85 p., incl., illus., tables, 113 refs.

Unclassified Report

The future use of radar in making specific-property determinations of the lunar surface is dependent upon knowledge of (a) the effects of lunar atmospheric conditions on radar propagation/operation and (b) radar reradiation signatures of possible lunar surface materials. If assessment of radar potentialities for exploration of the moon is to be made, theoretical analyses must be performed to determine possible effects that might be produced on radar propagation/operation if extreme-value estimates for lunar environmental factors are assumed to be correct. Based on currently available data and methods of analysis, such effects are shown to be relatively minor. In view of this determination and the embryonic status of radar terrain analysis, (which does not permit reliable interpretation of detailed measurements), fairly gross radar reradiation measurements of postulated lunar materials can be of great value. Radar frequencies at or near X-band (3 cm) and far-field operation are best suited for obtaining these data. Relatively simple facilities appear adequate, but radar reradiation measurements and theoretical determinations might require verification in a facility capable of simulating selected lunar atmospheric and surface conditions. In

1. Lunar Environment
2. Radar
3. Laboratory Simulation
I. AFSC Project 7698, Task 769803
II. Contract AF 19(628)-480
III. Texas Instruments Incorporated, Dallas, Texas
IV. F. E. Kinsman, J. R. Van Lopik
V. In ASTIA collection

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